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Contribution to food loss and waste management under a life cycle Nexus thinking approach

Contribución a la gestión de las pérdidas y desperdicios de alimentos bajo un enfoque de pensamiento Nexus del ciclo de vida

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Daniel Hoehn Capracci

Directores de Tesis:

Dr. Rubén Aldaco García

Dra. María Margallo Blanco

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Motivation

This Thesis was conducted within the framework of the Ceres-Procon Project "*Food production strategies for the mitigation of climate change: towards a circular food economy*". Ceres-Procon was a 4-year Spanish I+D+i project, funded by the Spanish Ministry of Economy and Competitiveness, which started in 2016 (CTM2016-76176-C2-1-R) (AEI/FEDER, UE).

The project was focused on the impacts of climate change, as one of the major challenges faced by society nowadays. In this framework, the options for climate change mitigation should extend to strategies specific to the food industry, as it is a sector generating one third of the total greenhouse gas (GHG) emissions. In addition, the reduction of fuels consumption and other actions related with production and consumption systems must be considered. In this regard, in a global context marked by an uptrend of such emissions from the food productive sector, the actions should be linked to an approach of food production and consumption strategies introducing food circular economy and food habit change strategies.

The project was in accordance to the European Sustainable Production and Consumption Policy, and also in accordance to the Challenges established by the Horizon 2020 Program. These Challenges focus, on one side, on food safety and quality, and natural resources sustainability. On the other side, on climate change mitigation actions and the efficiency in resources and raw materials use. In the context of food production, climate change mitigating strategies should focus on the definition of food biological cycle strategies by implementing on food the principles of the circular economy for the reduction of resource and raw materials consumption, and food spoiling along the supply chain. Moreover, the analysis of micro and macro nutrients losses for its transformation in other food sources must be done.

On the other hand, this Thesis has been made under the umbrella of the Doctoral Program in Chemical, Energy and Process Engineering at the University of Cantabria. The general objectives of the program are focused on fostering the development and the innovation skills through knowledge in Chemical and Energy Engineering.

In all this framework, this Thesis aims to contribute to the identification of the environmental impacts and main hotspots of the FLW generation and management in Spain. In addition, the six chapters presented aim to contribute to the academic community attention introducing some methodological issues related to life cycle assessment (LCA) of food. This Thesis is a compendium of papers published or accepted for publication in international scientific journals, fulfilling the requirements of the Department of Chemical and Biomolecular Engineering for the elaboration of a Thesis as a compendium of publications. During the elaboration of this Thesis, two research stays of two months (May-June 2019) and of one month (March 2021) were conducted at the University College of London (UCL), under the supervision of Dr. Aiduan Borrion, and at the University of Aveiro (UA), under the supervision of Dr. Paula Quinteiro, respectively.

The papers included in this Thesis are listed as follows:

1. García-Herrero I, Hoehn D, Margallo M, Laso J, Bala A, Batlle-Bayer L, Fullana P, Vazquez-Rowe I, Gonzalez MJ, Durá MJ, Sarabia C, Abajas R, Amo-Setien FJ, 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.
2. 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, 767.
3. Aldaco R, Hoehn D, Laso J, Margallo M, Ruiz-Salmón I, Cristobal J, Kahhat R, Villanueva-Rey P, Bala A, Batlle-Bayer L, Fullana-i-Palmer P, Irabien A, Vázquez-Rowe I **(2020)** Food waste management during the COVID-19 outbreak: a holistic climate, economic and nutritional approach. *Sci. Total Environ.* 742, 140524.
4. Hoehn D, Laso J, Cristóbal J, Butnar I, Borrion A, Bala A, Fullana-i-Palmer P, Vázquez-Rowe I, Aldaco R, Margallo M **(2020)** Regionalized

Strategies for Food Loss Management in Spain under a Life Cycle Thinking Approach. *Foods* 9(12), 1765.

5. Hoehn D, Margallo M, Laso J, Ruiz-Salmón I, Batlle-Bayer L, Bala A, Fullana-i-Palmer P, Aldaco R **(2021)** A novel composite index for the development of decentralized food production, food loss, and waste management policies: a Water-Climate-Food Nexus Approach. *Sustainability* 13, 2839.
6. Hoehn D, Laso J, Margallo M, Ruiz-Salmón I, Quiñones A, Amo-Setién FJ, Vázquez-Rowe I, Bala A, Batlle-Bayer L, Fullana-i-Palmer P, Aldaco R **(2021)** Introducing a degrowth approach to the circular economy policies of food production and food loss and waste management: towards a circular bioeconomy. *Sustainability* 13, 3379
7. Hoehn D, Margallo M, Laso J, Ruiz-Salmón I, Quinteiro P, Batlle-Bayer L, Fullana-i-Palmer P, Aldaco R **(2021)** Water footprint assessment for best-regionalized strategies for food loss and waste management in Spain (*in press*).

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List of nomenclature and acronyms

AC	Aerobic composting
AD	Anaerobic digestion
AD&C	Anaerobic digestion and composting
ADP	Abiotic depletion potential
AP	Acidification potential
BA	Botton ash
BAU	Non-compliance with the Paris Agreement targets
DS	Domestic supply
E-FLW	Economic food loss and waste
EEL	Embodied energy loss
EC	European Commission
EU	European Union
EP	Eutrophication potential
EROI	Energy Return on investment
EROI$_{ce}$	Energy return on investment - Circular economy
FAO	Food and Agriculture Organization
FBS	Food balance sheet
FCB	Food co-products and by-products
FEL	Food energy loss

FGT Flue gas treatment

FLW Food loss and waste

FL Food loss

FW Food waste

FLW$_{-ctog}$ Food loss and waste from craddle to gate

FLW$_{-gtog}$ Food loss and waste from gate to grave

FSC Food supply chain

F2F Farm to Fork Strategy

FU Functional unit

GHG Greenhouse gas

GHG-FLW Greenhouse gas emissions through food loss and waste

H Households

HT Human toxicity

GWP Global Warming Potential

ISO International Organization for Standarization

LCA Life cycle assessment

LCI Life cycle inventory

MFA Material flow analysis

MSW Municipal solid waste

NFLWF Nutritional Food Loss and Waste Footprint

NFLF Nutritional Food Loss Footprint

NFLW Nutritional Food Waste Footprint

N-FLW Nutritional food loss and waste

NRF9.3 Nutrient Rich Foods

OECD The Organization for Economic Cooperation and Development

PED Primary energy demand

POCP	Photochemical Ozone Creation Potential
SCR	Selective Catalytic Reduction
SNCR	Selective Non-catalytic Reduction
SDG	Sustainable Development Goals
2DS	Compliance with the Paris Agreement targets

Glossary

Allocation - Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.

Anaerobic digestion - A continuous two-steps process, where the first stage is a high-solid plug-flow reactor operating at thermophilic temperature and the second a completely stirred tank reactor at mesophilic temperature. The total retention time of substrates is about 100 days. The main product is biogas, with an assumed 60% methane content. After it, methane is combusted in an engine to produce electricity.

Aerobic composting - It considers closed halls or so-called composting boxes or rotting tunnels. The input waste is assumed as an average mixture of biodegradable waste consisting of biodegradable garden and park waste, as well as a 35% content of food and kitchen waste. For the selective collection fraction, the composting system includes the energy requirements of a mechanical separation unit.

Energy flow analysis - The quantification of the energy/resources flow, loss in a system. It is considered the primary energy demand of each of the four stages in which the food supply chain is divided (agricultural production, processing and packaging, distribution and consumption).

Embodied energy loss - The primary energy invested in producing food loss and waste.

Food energy loss - The nutritional energy of the food loss and waste.

Food loss - The decrease of the 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 and packaging stages).

Food loss and waste - The food loss or waste generated at every stage of the food supply chain.

Food waste - The discarded food occurring at the end of the food supply chain (retail and final consumption – related to retailers´ and consumers´ behavior).

Food supply chain - The steps of agricultural production (including post-harvesting), processing and packaging, distribution (including transportation) and consumption (composed of extra-domestic and household consumption), from "cradle to consumer".

Functional unit - Quantified performance of a product system for use as a reference unit.

Incineration (thermal treatment) - Many stationary or mobile technical unit and equipment dedicated to the thermal treatment of wastes with or without recovery of the combustion heat generated.

Landfill with biogas recovery - Includes biogas and leachate treatment and deposition. Sealing materials (e.g. clay or mineral coating) and diesel for the compactor were also included. 17% of the biogas naturally released is 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 FLW was assumed.

Life cycle assessment (LCA) - Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Life cycle impact assessment - Phase of life cycle assessment in which the inputs and outputs data collected in the life cycle inventory are translated into an impact indicator results related to human health, natural environment, and resource depletion.

Life cycle inventory analysis - Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Material flow analysis - The quantification of the mass/resources flow, loss in a system.

Municipal solid waste - Materials we use and then throw away, such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries. This comes from our homes, schools, hospitals, and businesses.

Primary energy demand - Primary energy invested in the production of food.

System boundary - Set of criteria specifying which unit processes are part of a product system.

Waste - Substances or objects which the holder intends or is required to dispose of.

Waste management - The collection, transport, recovery, and disposal of waste, including the supervision of such operations and the after-care of disposal sites, and including actions taken as a dealer or broker.

Waste-to-energy - The conversion of non-recyclable waste materials into useable heat, electricity, or fuel through a variety of processes, including combustion, gasification, pyrolization, anaerobic digestion, and landfill gas recovery.

Abstract

The current system of exploitation of natural resources to satisfy the demand for food is among the main causes of environmental degradation, also threatening the food security and sovereignty of the world population. One of humanity's biggest challenges over the next decades will continue to be meeting the global nutritional demand, reducing pressure on food resources and greenhouse gas emissions. In this sense, the general challenge will consist of, in addition to a fairer and more equitable redistribution of production and consumption, the redesign of food systems, promoting sustainable eating patterns and limiting the food loss and waste.

This Thesis aims to contribute to the identification of the main sources of food loss and waste generation in Spain, as well as the environmental impacts associated with both their generation and their management. All this in order to assist in the decision-making by selecting the best strategies for the production and management of food loss and waste. This Thesis presents a methodological approach that combines life cycle thinking and the Water-Climate-Food (WCF) Nexus approach to address the challenges that arise in each of the stages of the food supply chain, and for each of the different fractions of food loss and waste.

The WCF Nexus seeks synergies and trade-offs between the exploitation of water resources, the food production and consumption, and the associated climate impacts. The developed methodology aims to be applicable in different contexts and levels, integrating, with a holistic approach, the WCF Nexus and life cycle assessment.

Resumen

El sistema actual de explotación de los recursos naturales para satisfacer la demanda de alimentos se encuentra entre las principales causas de la degradación ambiental, amenazando además la seguridad y la soberanía alimentaria de la población mundial. Uno de los grandes desafíos de la humanidad durante las próximas décadas seguirá siendo satisfacer la demanda nutricional global, reduciendo la presión sobre los recursos alimentarios y las emisiones de gases de efecto invernadero. En este sentido, el desafío general consistirá en, además de una redistribución de la producción y el consumo más justa y equitativa, el rediseño de los sistemas alimentarios, promoviendo patrones alimentarios sostenibles y limitando las pérdidas y los desperdicios de alimentos.

Esta tesis doctoral tiene como objetivo contribuir a la identificación de los principales focos de generación de pérdidas y desperdicios alimentarios en España, así como los impactos ambientales asociados tanto a su generación como a su gestión. Todo ello con el fin de asistir en la toma de decisiones mediante la selección de las mejores estrategias para la producción y gestión de las pérdidas y desperdicios de alimentos. Esta tesis doctoral propone un enfoque metodológico que combina el pensamiento de ciclo de vida y el enfoque de Nexo Agua-Clima-Alimentación (WCF) para abordar los retos y desafíos que se presentan en cada una de las etapas de la cadena de suministro de alimentos, y para cada una de las distintas fracciones de las pérdidas y desperdicios alimentarios.

El Nexo WCF busca establecer sinergias y compensaciones entre la explotación de los recursos hídricos, la producción y el consumo de alimentos, y los impactos climáticos asociados. La metodología desarrollada pretende ser aplicable en diferentes contextos y niveles, integrando, con un enfoque holístico el Nexo WCF y el análisis de ciclo de vida.

CHAPTER 1

Food loss and waste: contextualization and Thesis approaches

1.1. Food loss and waste management

1.1.1. Overview

The current pattern of natural resources exploitation to meet humanity's demand for food is among the major causes of environmental degradation and threatens long-term food security. In recent years, progress has been made in improving food production sustainability and nutrition security. Nevertheless, food supply chain (FSC) processes, from the farm to the consumption stages, have been highlighted as one of the most polluting daily activities (Carlsson-Kanyama et al., 2003). The impact along food product life cycle is mainly due to several factors, such as the high degree of mechanization, the use of agrochemical products in agriculture, the long distances in distribution routes, the overpacking of products, and the growth of consumption of processed food. Regarding the last one, those products are called fourth and fifth range products, which are ready to be consumed and sold refrigerated.

All these elements have entailed an increase in the energy consumption throughout the entire supply chain, transforming it from a net producer to a net consumer of energy (Infante-Amate and González de Molina, 2013). It is estimated that nowadays around 30% of the world's total energy consumption is due to the food system (FAO, 2011). According to the European Commission (EC) (2016), industrial food activities require approximately 26% of the European Union´s (EU) final energy consumption. However, this is not a new phenomenon. In fact, Pimentel and Pimentel (2008) found that in the energy crisis of the 70s the energy efficiency of modern food production was declining. Over time, the energy inputs began to be higher than the energy outputs (Martínez-Alier, 2011), and according to Cuellar and Webber (2010), Lin et al. (2011) and Vittuari et al. (2016), nowadays the FSC requires on average 10-15 kJ of fossil fuel to produce 1kJ of food. From the whole supply chain, the high-energy intensity of agriculture has meant an enormous increase in the consumption of fossil fuels. Nevertheless, this fact is common in all phases of the FSC and it varies depending on the type of product and level of processing. Global energy consumption is also expected to rise by 50% in 2050 (Alexandratos and Bruinsma, 2012). The energy intensity of modern systems represents a major issue in a current framework of decreasing limited resources, and growing population (Markussen and Østergård, 2013).

On the other hand, 70% of the world's freshwater withdrawals consumption (as well as 78% of the eutrophication in oceans and freshwater reserves), and around 20-30% of the anthropogenic greenhouse gas (GHG) emissions are due to the FSC, being agricultural production the most critical stage (Garnett, 2011, Vermeulen et al., 2012, Ritchie and Roser, 2020). Additionally, in a global context of increasing population, food production and global water withdrawals are expected to increase by 60% and 50%, respectively, until 2050 (Vora et al., 2017). Therefore, the FSC efficiency has been identified as an essential means to enhance food security, while reducing pressure on natural resources (Chaboud and Daviron, 2017).

In this framework, after years of awareness, food loss and waste (FLW) has gradually become a mainstream concern searching for that efficiency (Vázquez-Rowe et al., 2019). When defining FLW, the FAO considers a distinction between food loss (FL) and food waste (FW). On one hand, FL is considered as the decrease of the 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). On the other hand, FW is considered as the discarded food occurring at the end of the FSC (retail and final consumption – related to retailers and consumers behavior) (FAO, 2011), which is discarded before or after expiration date (Wunderlich and Martínez, 2018). Albeit, usually both terms are added together as FLW when quantifying them for further analysis (Corrado and Sala, 2018). In this Thesis, FLW refers to its generation at every stage of the FSC (FAO, 2019b), considering the FAO distinction along the FSC (FL in the early stages, FW in the final stages) as represented in Figure 1.1.

Figure 1.1 Representation of the division between food loss (FL) and food waste (FW), included in the food loss and waste (FLW) concept used in this Thesis.

FLW has central consequences on the energy balance on the FSC leading to a significant environmental impact in terms of inefficient use of natural resources, biodiversity and habitat loss, soil and water degradation, and GHG emissions (Vittuari et al., 2016). It is also directly related to food security and presents nutritional and ethical issues, as 795 million people suffer from undernourishment (FAO, 2015), and it is projected that by 2050 the world population will reach 9.8 billion persons (UN, 2017). Kummu et al. (2012) estimated that the nutritional energy lost in the FSC would be enough to feed around 1.9 billion people, and approximately half of those losses and wastes could be prevented. Thus, FLW supposes a missed opportunity to feed the world's growing population (MAGRAMA, 2013). In this sense, social pressure has been also increasing to overcome these problems through the reduction in the generation of FLW, as well as by developing technologies for energy recovery, leading to sustainable development (Tanczuk et al., 2017).

Many studies have assessed the FLW along the FSC. The study of Gustavsson et al. (2011) carried out by the Food and Agriculture Organization of the United Nations (FAO) is the most highly cited work. According to that report, around a third of all food produced globally is lost or wasted (1.3 billion of tons per year). This value was reinforced by the OECD, the Organization for Economic Cooperation and Development (OECD, 2017), which stated that more than a third of the food produced is wasted, involving around 38% of the energy embedded in its production. As represented in Figure 1.2, the distinction of FL and FW makes clear that the composition of the total FLW between the different regions along the world has a high variation regarding the fractions corresponding to FL or FW. In the same line, while the per capita proportions of FL are relatively similar in all the regions, the wasted food in industrialized regions is around 12 times higher than in developing countries (OECD, 2017). Nevertheless, both fractions require strategies for their reduction as a key to achieving sustainability, which has been widely recognized in the literature (Lemaire and Limbourg, 2019). More concretely, in Europe and North America, the per capita FLW reached 280 kg/year and 300 kg/year, representing FL 68% and 60% of the total amount, respectively. This means that, on average in industrialized countries, around 40% of FLW take place at retail and consumer levels. On the other hand, FLW per capita in Sub-Saharan Africa and South/Southeast Asia were 170 kg/year and 120 kg/year, respectively. In this case, FL represented more than 90% of the total FLW, with low contribution of the last stages of the FSC (Laso et al., 2021).

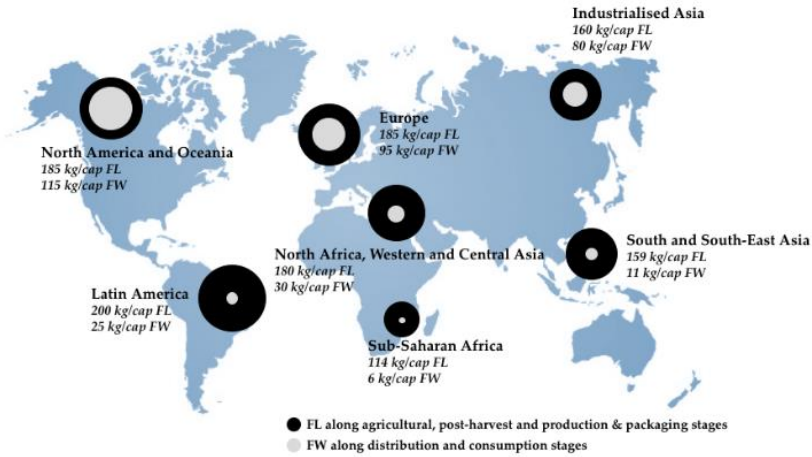

Figure 1.2 Global FL and FW measured in kg per capita in 2011. Figure presented in Laso et al. (2021).

At European level, under the premise that climate change is a fundamental threat to world food security, sustainable development and poverty eradication, the FUSIONS project (Food Use for Social Innovation by Optimizing Waste Prevention Strategies) estimated at 88 million tons and 143 billion euros the FLW generation (Stenmarck et al., 2016). This value represents approximately 20% of all food production and consumption (FUSIONS, 2016). Specifically, Spain has the seventh highest level of FLW in the EU, with around 7.7 million tons, after the United Kingdom (14.4 million tons), Germany (10.4 million tons), the Netherlands (9.5 million tons), France (9.1 million tons), Poland (9.0 million tons) and Italy (8.8 million tons) (MAGRAMA, 2013). These values could be higher by a harmonization in the definition of FLW and in the collection of FLW generation data, as suggested by Montagut and Gascón (2014). In this regard, in the early stages of the FSC (agricultural production, post-harvest and processing and packaging), the loss of non-edible animal and plant products, which are not originally intended to be eaten by humans, is often not considered as FLW, even if they are not re-used. Even though this, they may have implications for food security or for the environment (FAO, 2019).

1.1.2 Regulations, campaigns and strategies

Different regulations and strategies have been developed to meet sustainability objectives in the FSC regarding the generation of FLW and its management. All it, aiming to improve the agricultural production systems, to change the diets, to implement demand-side measures, and to achieve reductions of FLW generation (Alexander et al., 2017). At a global policy level, the initiative "Save Food", led by the FAO, started in 2011. It promoted the prevention and reduction of global FLW by successive measures that build upon each other. In 2015, the United Nations member states adopted the Sustainable Development Goals (SDG). The most connected goal with the food and FLW systems is the SDG12 (to ensure sustainable consumption and production patterns). More concretely, the SDG12.3 is aiming to halve FW at the retail and consumer level by 2030 and to reduce FL along the production, processing and packaging chains.

Moreover, other goals have also direct linkages with the production of food and the generation of FLW. SDG2 aims to end hunger, to achieve food security and improved nutrition, and to promote sustainable agriculture; SDG6 wants to ensure availability and sustainable management of water and sanitation for all; SDG7 aspires to ensure access to affordable, reliable, sustainable, and modern energy for all; and SDG13 aims to take urgent action to combat climate change and its impacts. Those goals connect with the three pillars of the Water-Climate-Food (WCF) Nexus that will be considered in the methodologies developed along the Thesis (as seen in Figure 1.3). In order to meet the SDG linked to food and FLW systems, by using a WCF Nexus thinking approach, policy-makers are encouraging widespread adoption of certain practices (Poore and Nemeek, 2018).

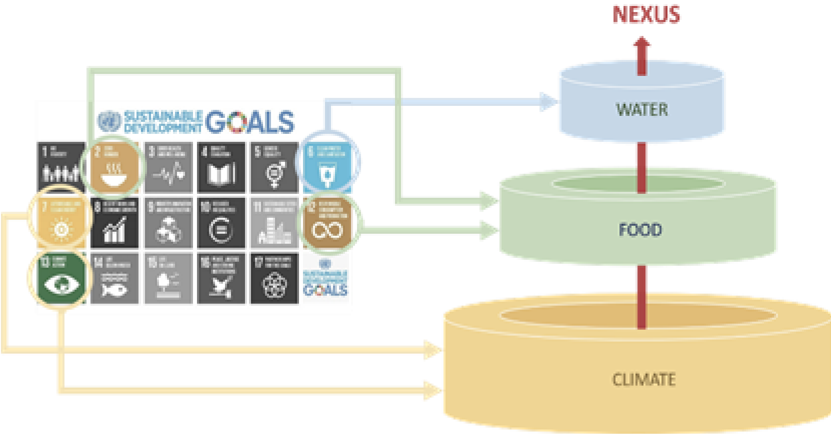

Figure 1.3 The sustainable development goals of the FAO, which are directly linked with the production of food, the generation of FLW, and with a Water-Climate-Food Nexus thinking approach.

At EU level, the provision of safe and nutritious food within an efficient, competitive and sustainable global market is also a central objective (EC, 2010). Conversely, most of the European food policies are included within the waste policy framework. Such is the case of the Waste Framework Directive (EC, 2008), which establishes waste prevention at the top of the "waste hierarchy" (Figure 1.4), but does not properly reflect actions applicable to FLW. In addition, the EC, mainly due to the increasing population growth, has estimated the impact of waste policies on FLW reduction as negligible (Monier et al., 2010). To face this challenge, the EC adopted the Circular Economy Package (EC, 2015a, EC 2019a), which aims to help European producers and consumers to a transition towards more sustainable resources use. The FUSIONS project contributed to these ambitious goals, providing guidelines for a European common policy framework on FLW prevention. Nevertheless, there is still a need of adopting a legally binding FLW hierarchy that interprets and applies the waste in the context of FLW (FUSIONS, 2016). However, beyond reductions in FLW, the EC is using as a reference the waste hierarchy, positioning prevention at the top (Cristobal et al., 2018). In the same line, the EC requires the member states to monitor and report on FLW generation and to implement national FLW reduction programs (EC, 2008).

While the generation of GHG from the food sector are expected to rise due to a growing world population demanding increasingly richer diets, with large amounts of meat and dairy products, the decomposition of FLW in landfills also represents an important non-point source of GHG emissions. In this regard, the Directive 1999/31/EC on the landfill of waste asked the EU Member States to reduce the share of landfilled biodegradable municipal waste to 75% in 2005, to 50% in 2009 and 35% in 2016 in relation to 1995 (EC, 1999). However, there is a high diversity between countries in terms of waste management strategies (including FLW). For instance, Denmark, Austria, and Germany are reference countries in terms of avoiding landfilled waste (Castillo-Giménez et al., 2019). Nevertheless, while Denmark is focused on strategies of waste incineration (Danish Ministry of the Environment, 2013), Austria is developing decentralized aerobic composting (AC) systems (World Bank Group, 2016), and Germany is investing in anaerobic digestion (AD) plants for organic waste (FNR, 2019).

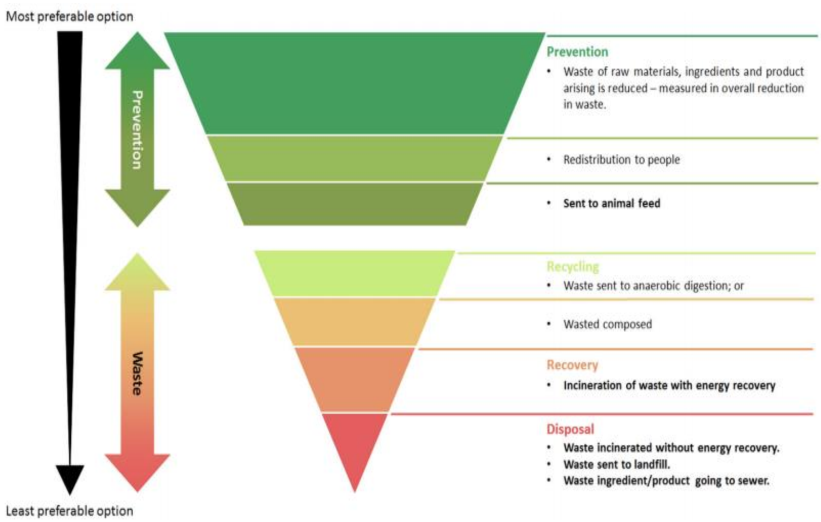

Figure 1.4 Graphical representation of the waste hierarchy for food and beverages adapted from the Waste Framework Directive 2008/98/EC. Presented in Laso et al., 2018a.

In 2020, the “Farm to Fork Strategy” (F2F) for sustainable food (EC 2020a), was presented aiming to make food systems fair, healthy and environmentally friendly. All it, in order to meet the increasing challenges of feeding the world's population, raising food security, and achieving environmental sustainability (Foley et al., 2011,), in a context where, as previously mentioned, the global demand for food is expected to increase for at least until 2050 (Godfray et al., 2010). F2F is a key component of the European Green Deal, released in 2019, that is the roadmap for making the EU economy sustainable with the final goal of turning Europe in a climate-neutral continent by 2050 (EC, 2019b). Besides, F2F is also central to the United Nations commitment of halving the per capita FW at retail and consumer level by 2030 and reducing FLW along the FSC (SDG 12.3) (UN, 2019). Thus, F2F foresees specific measures such as proposing for EU-level legally binding targets for FLW reduction by 2023 and reviewing the EU rules on date marking (‘use by’ and ‘best before’ dates) by the end of 2022 (EC, 2020a).

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. The special attention is given to food packaging solutions, with environmentally friendly re-usable and recyclable materials. All it, using life cycle assessment (LCA) to choose the best option (Abejón et al., 2020), and to contribute to FLW reduction. In addition, the EC is revising 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 is aiming to strengthen educational messages on the importance of reducing FLW within school schemes.

At national and sub-national levels, more than a hundred initiatives have been implemented in the EU countries to reduce FW through awareness campaigns, and training and research programs (Secondi et al., 2015, EC, 2015b). Some prominent examples of these programs include “More Food, Less Waste”, in Spain, “Love Food, Hate Waste” from Waste and Resources Action Programme (WRAP), in UK, the Milan Protocol from the Foundation Barilla Centre for Food and Nutrition, in Italy, and “Feeding the 5000” from the NGO Feedback, in UK (as represented in Figure 1.5).

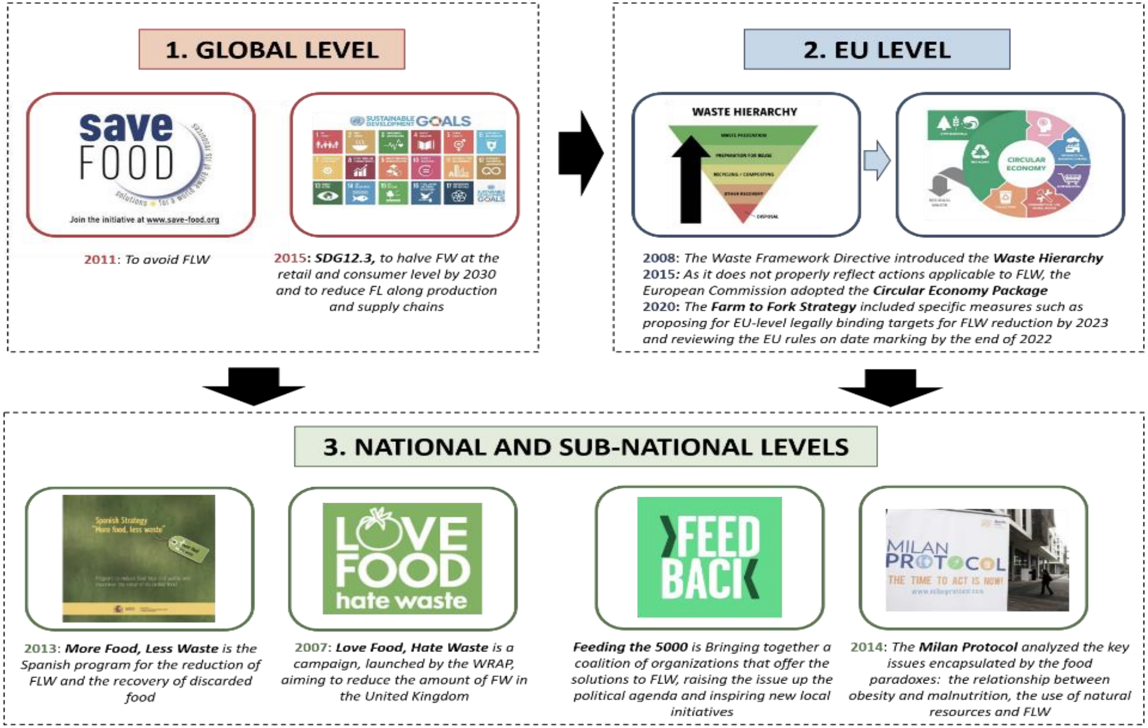

Figure 1.5 Overview of the more representative regulations, campaigns, and strategies regarding FL and FW, at global, European Union, national, and sub-national levels.

1.1.3 Strong short-term changes: the COVID-19 outbreak

The emergent coronavirus disease, COVID-19, is presenting 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 ceased worldwide in some way or another between March and May 2019. Lockdown measures in Spain affected in that period different supply chains, leading to a reduction of economic growth or a foreseeable economic recession. The FSC was not exempt from these disruptions, and, since the beginning of the lockdown period COVID-19 created huge shifts in terms of food access, food security and FLW generation (ReFED, 2020). Accordingly, the exceptional nature of food production and consumption habits due to COVID-19 may influenced on the generation of FLW along the supply chain (Jribi et al., 2020) and on other aspects of sustainability (Song et al., 2019). 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.

In Spain the Ministry of Agriculture, Fisheries and Food evaluated the impact of COVID-19 on Spanish consumers´ food preferences and behaviors during the lockdown period. The study showed that in general terms household consumption increased significantly in the first weeks (in March, April and May of 2020) across all food categories. Spanish consumers were 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, 2020). These behavioral patterns implied not only changes in the FSC and in the generation of FLW, but also repercussions on the dietary pattern, which may have been detrimental to the health and also other environmental attributes offered by the Spanish Mediterranean diet (Batlle-Bayer et al., 2019), triggering obesity, sleep disruptions or impacts on the immune system (Muscogiuri et al., 2020). Moreover, the real cost of a healthy diet might rose because of the increase in the cost of perishable commodities, which would have a particularly adverse impact on lower-income households and slowed the progress towards complying with the SDG (FAO, 2020).

1.1.4 Life cycle assessment under a Nexus approach

The previous sections presented the problematic of FLW generation and the environmental impacts associated. Therefore, FLW has to be properly management in order to reduce its environmental impacts, and life cycle thinking considering the whole FSC, can help policy makers to choose the best environmental options (JRC, 2014). LCA is defined as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO, 14040). It is a powerful tool for assessing the environmental performance of a product, process, or activity from raw material extraction ("cradle"), to end of life ("grave"). It is often used to support decision-making in order to identify cleaner and more sustainable alternatives in the process design activity (Rebitzer et al., 2004).

As represented in Figure 1.6, LCA is a standardized tool that should be applied using the ISO 14040 (ISO 2006a) and 14044 (ISO 2006b) standards, where LCA is described as a four-phase process:

a) **Goal and scope definition**. This step defines the intended application of the study, the system description, the functional unit, the system boundaries, the allocation procedures and the assumptions. The goal shall unambiguously state the intended application, the reasons for carrying out the study and to whom the results of the study are intended to be communicated. The scope should be sufficiently well defined to ensure that the breadth, the depth and the detail of the study are compatible and sufficient to address the stated goal. The scope of an LCA study shall clearly specify the functions of the system being studied. A functional unit is a measure of the performance of the functional outputs of the product system. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. The system boundaries determine which unit processes shall be included within the LCA. Several factors determine the system boundaries, including the intended application of the study, the assumptions made, the cut-off criteria, the data and cost constraints, and the intended audience. Allocation procedures are needed when dealing with systems involving multiple products (e.g., multiple products from petroleum refining). The materials and energy flows as well as the associated environmental releases shall be allocated to the different products according to clearly stated procedures, which shall be documented and justified.

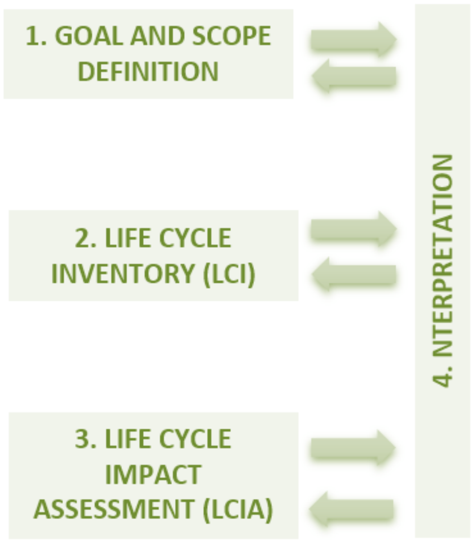

Figure 1.6 Steps of a life cycle assessment according to the ISO 14041 (2006).

b) **Life cycle inventory analysis**. Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. These inputs and outputs may include the use of resources and releases to air, water and land associated with the system. Interpretations are drawn from these data, depending on the goals and scope of the LCA. These data also constitute the input to the life cycle impact assessment.

c) **Life cycle impact assessment**. The impact assessment phase of LCA aims to evaluate the significance of potential environmental impacts using the results of the life cycle inventory analysis. In general, this process involves associating inventory data with specific environmental impacts and attempting to understand those impacts. The level of detail, choice of impacts evaluated and methodologies used depends on the goal and scope of the study.
d) **Interpretation**. Is the last step, in which the findings from the inventory analysis and the impact assessment are combined together. The findings of this interpretation may take the form of conclusions and recommendations to decision-makers, consistent with the goal and scope of the study.

As already introduced in Section 1.1.2, additionally, the life cycle thinking is combined with a WCF Nexus approach, towards a «*FLW management under a life cycle Nexus thinking approach*», as represented in Figure 1.7.

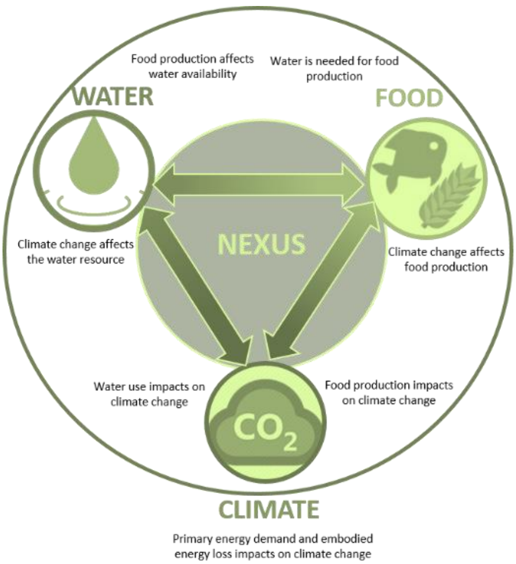

Figure 1.7 Conceptual diagram of the Water-Climate-Food Nexus.

In this line, according to Fernandes-Torres et al. (2019), the existing interdependences among the variety of sectors that sustain the global economy involve five relevant aspects:

i. The fundamental elements of water, energy, and food are interlinked.
ii. Economic sectors have a relation to at least one of the three aforementioned elements.
iii. Alterations in any of those elements cause chain reactions in segments associated with them.
iv. Negative impacts generated by the consumption of those elements are passed on to society.
v. The interdependences among those elements are increasingly apparent in this scenario of crisis and scarcity of resources.

In other previous studies in this field, energy is used to describe one of the Nexus pillars. Such is the case of the Energy-Water-Food Nexus assessment developed by Irabien and Darton (2016), regarding the Spanish greenhouse tomato production in the Almeria region (Andalusia). In this Thesis, the energy pillar has been transcribed in terms of Global Warming Potential (GWP) linked to the primary energy demand (PED) and the embodied energy loss (EEL) of FLW, along the whole supply chain. Thereby, the different assessments developed throughout the chapters are focusing in the WCF Nexus. All it, aiming to contribute to make visible the importance of considering the three elements of the Nexus when re-evaluating the best management models specifically, as well as formulating policies and projects. According to Simpson and Jewitt (2019), the Nexus framework is considered by many authors in both academic and grey literature as holding promise for guiding policy development and governance structures in a world that is facing climate change, population growth, and inequality in terms of access to resources. Consequently, the linking of Nexus assessments with the SDG is imperative. The main reasons behind the consolidation and growing visibility of the Nexus concept can be associated with insecurities and high impacts of water availability and overexploitation, energy use and its implications in terms of GHG emissions, and the food scarcity. In this sense, LCA is considered as an ideal tool for Nexus analysis, since it takes into account the entire production and consumption chain.

1.1.5 State of the art

In recent years, many studies have assessed the FLW generation and management, covering the three dimensions of sustainability: environment, society and economy. The environmental variable has been mostly assessed under a life cycle approach, including energy assessments. Laso et al. (2018b) used LCA and data envelopment analysis (DEA) to assess the efficiency of the Spanish agri-food system and to present improvement actions in order to reduce the energy use and the GHG emissions. Batlle-Bayer et al. (2020a) introduced a method to quantify environmental impacts together with nutritional values, including food affordability (Batlle-Bayer et al., 2020b). Moreover, 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, and its embodied GHG emissions, across different world regions for the period 2000–2015. Kim and Kim (2010) evaluated different FW disposal options from the perspective of global warming and resource recovery, whereas Slorach et al. (2020) analyzed the environmental and economic sustainability of five plausible scenarios for FW treatment in the UK. Furthermore, as not all food is of equal calorific and nutritional value, the nutritional content of FLW should be considered in the decision-making process (Bradshaw, 2018). In this regard, Vázquez-Rowe et al. (2019) 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. Only a few partial approaches have been found in the literature assessing nutritional and economic losses together, but do not explore the nature of this relationship. For example, Buzby and Hyman (2012) estimated the total amount and monetary value of FL in the United States and Kummu et al. (2012) quantified the global FL in terms of energy (kcal). Alexander et al. (2017) studied the global mass FL and the nutritional content of these losses in terms of energy and proteins. 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. Additionally, FLW have also been widely addressed under a Nexus approach (Laso et al., 2018a). The economic factor has been considered from a perspective of market potential for value-added surplus products (McCarthy et al., 2020). Regarding economic aspects, only a limited number of case studies have been reported in the literature, mostly related to municipal FLW management (De Menna et al., 2018). Moreover, an economic and the environmental hierarchy has been presented (Redlingshöfer et al., 2020), a life cycle cost thinking approach has been implemented (De Menna et al., 2018) or even LCA and life cycle costing have been combined (De Menna et al., 2020; Slorach et al., 2019). Finally, the social aspect has been studied to include important aspects, such as food security, food safety and nutrition. Makov et al. (2020) explored whether the sharing economy can provide meaningful assistance to reducing FW in a relatively low-impact and environmentally-sound way. On the other hand, Morone and Imbert (2020) stated FW as representing a valuable option, due to the possibilities of producing a wide range of biobased products ranging from biofuels to bioplastics. A broader representation of the state of the art of the FLW generation and management studies is presented in Table 1.1.

In this sense, although global and national studies in FLW generation and management field are very useful to provide significant data, they often fail to describe individual singularities. Moreover, national data for specific regions are often not available or lack for sufficient quality (Monier et al., 2010; Stenmarck et al., 2016). This is the reason why studies at national level are an up-coming trend in the literature (Caronna, 2011; Beretta et al., 2013; Halloran et al., 2014). The case study of Spain presented in this Thesis, aims to generate a high interest since the Mediterranean region has reached a level of environmental degradation that requires immediate action, despite being usually highlighted as a good example of balanced diet (UNEP, 2010). Scarce natural resources and increasing environmental impacts are the main reasons. Additionally, the majority of the Mediterranean countries rely on the biocapacity of foreign countries to satisfy their population´s demand for food (Galli et al., 2017).

Few studies have analyzed the situation in Spain in terms of FLW generation and management. This Thesis aims to assess the Spanish context at the national and regional levels, suggesting the best FLW management strategies in terms of environmental sustainability, and compare the current situation with international references and targets, in order to inspire policy-makers for future policies development regarding the FLW challenges.

Table 1.1 State of the art of similar studies and working conditions.

Authors	Year	Research	Goal	Region	Main results and conclusions
Quested and Johnson	2009	Kg CO_2 eq./t waste	Household food and drink waste	United Kingdom	4.5 t CO_2 eq./t waste
Hall et al.	2009	Nutritional loss and freshwater consumption of food waste	Energy content of nationwide food waste	United States	Food waste generation: more than 1400 kcal per person per day, more than one quarter of the total freshwater consumption and 300 million barrels of oil per year
Cuéllar and Webber	2010	Embodied energy loss (EEL)	Sustainability of meat based and plant-based diets	United States	Highest EEL of food waste: dairy products and vegetables
Gustavsson et al.	2011	Weight of food losses and waste	Differences between countries	Global	Direct relation between higher amounts of food waste and the industrialization level of the country
Berners-Lee et al.	2012	Greenhouse gas (GHG) emissions	Impacts of realistic dietary choices	Supermarket chain – northwest of England	Highest GHG emissions of food waste: fresh fruit, vegetables and salads
Kummu et al.	2012	Weight of food losses and waste and its nutritional energy loss	Food supply losses and the resources used to produce them	Global	Around one quarter of the produced food supply (614 kcal/cap/day) is lost (enough food for one billion extra people)
Rutten	2013	Economic loss	Comparison of different countries	Global	Food losses and waste in industrialised and developing countries: US$ 680 and US$ 310 billion
Buzby et al.	2014	Nutritional loss	Estimated amount, value, and calories of postharvest food losses	Retail and consumer levels in the United States	Food loss: 141 trillion calories per year. Meat, poultry, and fish (30 %), vegetables (19 %), dairy products (17 %)
Vázquez-Rowe et al.	2014	Edible Protein Energy Return on Investment (ep-EROI)	Ratio between energy inputs and energy provided	Seafood products in Galicia (Spain)	Highest ep-EROI: Small pelagic species

Table 1.1 (Cont.) State of the art of similar studies and working conditions.

Vittuari et al.	2016	EEL	Assessment of the Food Supply Chain	Italy	Highest EEL of food waste: meat, milk and fish
Spiker et al.	2017	Nutritional loss	Nutrient loss and comparison to gaps in dietary intake	Retail and consumer levels in the United States	Food wasted: 1,217 kcal, 33 g protein, 5.9 g dietary fiber, 1.7 µg vitamin D, 286 mg calcium, and 880 mg potassium per capita per day
Eriksson and Spångberg	2017	Carbon footprint and energy use	Impacts of different food waste management options	Fresh fruit and vegetables from supermarkets in Växjö (Sweden)	Reduction in GHG emissions and primary energy use by changes to more favorable options in the waste hierarchy
Abbade	2018	Nutritional loss	Rate of loss for the main food groups in the world	Global	The rate of loss remains constant or slightly growing. The amount of food losses would be enough to feed 940 million adult individuals
Scherhaufer et al.	2018	Environmental impacts of food waste	CO_2 eq./t waste	Europe	1.9 t CO_2 eq./t waste
Laso et al.	2018b	Energetic and environmentally efficiency	Assessment of the efficiency of the agri-food system	Spain	An average energy saving of approximately 70% is estimated in order to be efficient
García-Herrero et al.	2019	Nutritional and economic food losses and waste	Development of a nutritional cost footprint indicator combining nutritional and economic variables	Spain	Highest nutritional and economic food waste: agricultural production and fruits and vegetables
Vázquez-Rowe et al.	2019	Nutritional cost footprint	Assessment of the nutritional and economic efficiency of food loss and waste	Spain	Less efficiency: vegetables and fruits Main FW generation: agricultural production and consumption

Table 1.1 (Cont.) State of the art of similar studies and working conditions.

Chen et al.	2020	Nutritional and environmental losses	Nutritional and environmental footprint in food waste	151 countries	Highest mass loss: vegetables, cereals and fruits. Highest nutritional loss: cereals, fruits, vegetables and meat. Highest environmental impacts: cereals, fruits and vegetables
Wohner et al.	2020	Environmental and economic assessment	Impacts of food-packaging systems with a focus on food waste	Austria	Higher food waste resulted in higher environmental impacts but also higher value added to the economy
Laso et al.	2020	Nutritional and economic food loss and waste management	Multi-objective optimization to evaluate the economic and nutritional cost of food loss and waste	Spain	Higher economic and nutritional cost of food loss and waste: 80% in agricultural production (53.3%) and consumption (26.3%) stages Higher efficient categories: pulses and eggs

1.2. Thesis scope and objectives

The first chapter has been designed to be an introduction to the following chapters, providing to the reader an exhaustive overview of the key concerns about FLW generation and management in Spain, the LCA methodology, and a review of previous works developed in the same or similar fields of study. Chapter 1 achieves the **Objective 1**, identifying the problems linked to food systems in Spain, highlighting the need to improve its sustainability regarding the WCF Nexus, as well as in economic and social terms.

Chapter 2 covers several objectives to develop and implement methodologies for the quantification of loss of mass, energy, nutritional content and economic value in food systems. **Objective 2** aims to quantify the FLW, introducing specific calculation methodologies for different food categories and stages of the Spanish FSC. The **Objective 3** introduces the development and calculation of indicators of sustainable behavior that allow to evaluate the nutritional, the environmental (different impact categories) and the economic goodness of the different stages of the FSC. Finally, the **Objective 4** addresses the assessment of different FLW management alternatives under a food circular economy approach. The fourth chapter fulfills the same objectives, since the previously developed methodology is implemented in a real case study.

Due to the differences in the available management technologies and the composition of the FLW generated, this Thesis hypothesizes that the best FLW management strategy from an environmental point of view can be different in each Spanish region. Thereby, Chapter 3 presents the regionalized results of the assessment of different FLW management scenarios at each of the 17 regions (i.e. Autonomous Communities) in Spain. Therefore, different scenarios have been evaluated over time taking into account several environmental impact categories, and using energy mix projections of the potential situation from 2015 until 2040. This chapter answer to the goal of the **Objective 5** that aims to facilitate the decision-making process at regional level, suggesting scenarios that will lead to the environmental sustainability, as well as to reduce the environmental cost of food production systems in Spain.

The fifth chapter assesses, firstly, the degrowth needed of the Spanish FSC and FLW management systems, and, secondly, implements the so-called SDG-Food index, for determining the level of compliance of the FSC system, and its associated FLW generation, with the five described SDG, related to food systems. All it aiming to introduce practical methodologies aspiring to be useful for policy-makers when analyzing the situation in Spain regarding to international references. Thereby, it is aimed to contribute to the **Objective 6** of this Thesis, by defining strategies in the biological cycle of food through the application of the principles of the Circular Economy. Moreover, a methodology to measure the necessary degrowth in the Spanish FSC, as well as an indicator to measure the level of compliance with five SDG, were developed and applied to Spain. It again contributes to the aforementioned **Objective 3**. Additionally, both the pillars that make up the degrowth assessment, as well as the data used for developing the SDG-Food index assessment, are based on a WCF Nexus approach, linking with the **Objective 7** of assessing and developing strategies for FLW generation and management under a life cycle Nexus thinking approach.

Furthermore, the **Objective 8** highlights the need to find a more sustainable way of eating, looking for healthier and more respectful diets with the environment, that specifically contribute to the mitigation of climate change. This objective has been covered in Chapters 2 and 5, which assessed different diets regarding their mass, economic and energy loss, as well as their placement in the SDG-Food index scale.

Finally, based on the results of the critical analysis, the main conclusions related to the methodological and technical problems concerned with the application of LCA to the food sector, as well as lessons learnt and future work under development are presented (as represented in Figure 1.8).

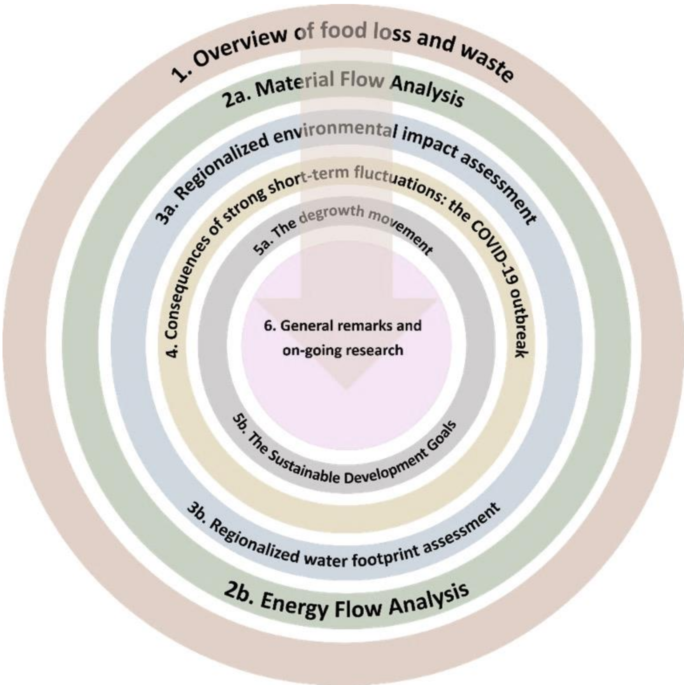

Figure 1.8 Diagram of the Thesis structure.

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CHAPTER 2

Mass, nutritional, economic and energy assessment

2.1. Framework

This chapter based on two published papers covers the objectives 2, 3, 4, 5 and 8 of this Thesis. The **Objective 2** aims to quantify the FLW of the Spanish FSC, introducing specific calculation methodologies for different categories of food and different stages of the FSC. The **Objective 3** involves an analysis of nutrients losses and their possible transformation into other food sources. The **Objective 3** introduces the development and calculation of indicators of sustainable behavior that allow to evaluate the nutritional, the environmental (different impact categories) and the economic goodness of the different stages of the FSC. Finally, the **Objective 4** addresses the assessment of different FLW management alternatives under a food circular economy approach. Finally, the **Objective 8** highlights the need to find a more sustainable way of eating, looking for healthier and more environmentally friendly diets, contributing to climate change mitigation. The papers included in Section 2.2 and 2.3 are listed as follows:

1. García-Herrero I, Hoehn D, Margallo M, Laso J, Bala A, Batlle-Bayer L, Fullana P, Vazquez-Rowe I, Gonzalez MJ, Durá MJ, Sarabia C, Abajas R, Amo-Setien FJ, 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.
2. 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, 767.

2.2. On the estimation of potential food loss and waste reduction to support sustainable production and consumption policies

2.2.1 Introduction

In a framework of worldwide increasing awareness regarding the importance of FLW prevention and management, the research developed in this section focuses on the need of future strategies to reduce nutritional and economic FLW considering not only their quantification but also their ‘qualification’. In this sense, it is presented a methodology to calculate the so-called *Nutritional Food Loss and Waste Footprint (NFLWF) index* that assesses and balances the amount and nutritional and economic value of FLW. The quantity variable linked to the environmental dimension refers to the unnecessary pressure on natural resources caused by avoidable food production and wastage (Figure 2.1). The nutritional variable is directly related to the availability and access dimensions of food security. Finally, for economic impacts, reducing FLW would help all of the stakeholders to save money, especially to consumers, although it could involve trades-off for other stakeholders (Chaboud and Daviron, 2017). This methodology was applied to determine the potential reduction of FLW. Finally, this section presented a FLW management hierarchy based on a double pyramid that considers the NFLWF results for illustrating the prioritization needed by FLW management actions.

The study of this section is focused on the Mediterranean region, in particular on Spain, where although numerous initiatives have been implemented at national and sub-national levels (‘More food, less waste’, ‘Save Food’, ‘Food responsible consumption’) there is still a significant gap regarding the FSC losses and waste. Nevertheless, this methodology can be further applied to other similar regions providing an international scope to the study.

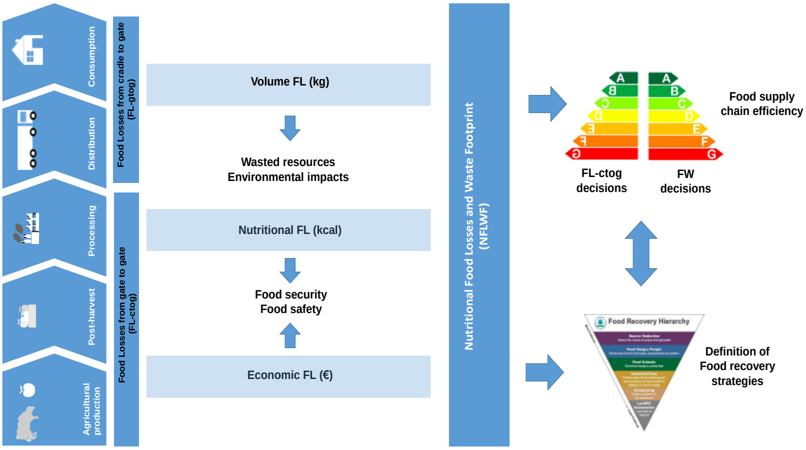

Figure 2.1 Conceptual diagram of the methodology to determine the Nutritional Food Loss and Waste Footprint (NFLFW) index.

2.2.2 Methodology

Definitions

Different definitions, measures and indicators have been reported in the literature in recent years, owing to the increasing awareness in facing the FLW management problem. To avoid confusion and make the results of this Thesis comparable to other studies, technical criteria widely agreed with the scientific community have been adopted. As suggested by Okawa (2015), one of the main problems for a quantitative analysis of FLW is the lack of harmonization on definitions and methodologies. Some studies include the rearing phase of animals within the system boundaries (Hartikainen et al., 2018), while others consider the timing definition from when commodities are ready for harvest/slaughter (Stenmark et al., 2016). The reason for considering the rearing phase lies in the fact that animals and fishes can be slaughtered for food production at any age, being the chosen age the economically optimal stage (Hartikainen et al., 2018). Conversely, harvesting time for crops is based on biological criteria. Some definitions consider FLW all the products originally intended for human consumption but not ingested

(Gustavsson et al., 2011; Beretta et al., 2013; FAO, 2014; Hartikainen et al., 2018), whereas others exclude food not consumed and redirected to animal feed from the definition (Stenmarck et al., 2016, Redlingshöfer et al., 2017). Edibility is also a criterion in disagreement. Some studies exclude inedible parts of food from the definition (Hartikainen et al., 2018) or state that inedible parts are excluded only when they have been separated in a processing step. Others authors include both edible and inedible parts (Stenmarck et al., 2016). Thereby, as introduced in Chapter 1, there is a lack of harmonization in the FLW terminology. 'FL, 'FW', and 'FLW' are the most used terms. Since this study relies heavily on the loss percentages reported by FAO (Gustavsson et al., 2013), the FLW definition used is based on the latest definition provided by FAO (2014):

(i) FLW refers to any substance, whether processed, semi-processed or raw, which was initially intended for human consumption but was discarded or lost at any stage of the supply chain. It concerns to every non-food used, including discarded food that was originally produced for human consumption and then recycled into animal feed.
(ii) System boundaries for crops start from which they are ready to be harvested, whereas food loss for meat refer to animal death during breeding. For fish, losses refer to discards during fishing. For milk, losses refer to sickness (mastitis) for dairy cows.

According to FAO's previous definition (Gustavsson et al., 2011), 'FL' occur at the beginning of the supply chain, while 'FW' is used for FLW taking place at the end of the supply value chain (retail and consumption), where most losses are due to wasteful behavior (Beretta et al., 2013). However, such distinction between supply stages losses does not reflect behavioral issues, since there are FLW taking place at primary production stage caused by the actions and behaviors at the retail stage (e.g. poor demand forecasting, late cancellation of orders, reinterpretation of product specifications resulting in rejected products). Therefore, although this section uses the terminology FLW to encompass both FL and FW occurring at every stage, it is distinguished between FLW from cradle to gate (FLW-ctog) at the front end of the supply chain (i.e. agricultural production, postharvest and processing), and FLW from gate to grave (FLW-gtog) at the consumer end (i.e. distribution and consumption), as represented in Figure 2.2. This distinction is not based on behavioral criteria, but in life cycle thinking approach, to provide a separated decisional framework for producers and consumers. Although recent EU policies aim to foster resource efficiency to help transition to a more sustainable use of resources, reduction targets often refer only to the consumption stage. Consequently, the assessment of FLW under a life cycle thinking approach can serve at the definition of specific targets for the different supply stages.

Furthermore, the distinction between ‘avoidable’ and ‘unavoidable’ FLW is done. Avoidable FLW is the amount of food thrown away because it is no longer wanted or has been allowed to go past its ‘best before’ or ‘expiration’ date. Unavoidable FLW are food parts, which are not and have not been edible under normal circumstances (e.g. egg shell, apple core, banana skin, and animal bones). This distinction can be subjective because what is considered edible depends on several factors such as culture, religion, social norms and personal preferences. In addition to that, harvesting, storage, transportation and processing losses that are not avoidable with best available technologies and reasonable extra costs can also be considered as unavoidable (Beretta et al., 2013).

Material flow analysis

Material flow analysis (MFA) quantifies the mass/resources flow, loss in a system, and facilitates in data reconciliation in a well-defined space and time (Padeyanda et al., 2016). An MFA can also be used for developing indicators to assess resource efficiency and sustainable development (Sakai et al., 2017); such is the case of the work developed in this section. Figure 2.2 outlines the material flow model used for quantifying the FLW throughout the FSC. According to it, FLW are estimated at five different steps of the supply chain ($1<j<5$):

(i) **Agricultural production** (j=1). This is the first stage of the FSC. For crop items, FL at this step are due to mechanical damage and/or spillage during harvest operation. For animal products, it refers to animal death during breeding, fish discards during fishing and milk losses owing to sickness for dairy cows.

(ii) **Postharvest handling and storage** (j=2). It refers to the amounts of commodity lost during handling, storage and transport between farm and processing or distribution. For meat commodities, it refers to death during transport to slaughter and condemnation at slaughterhouse.

(iii) **Processing and packaging** (j=3) consider spillage and degradation during industrial or domestic processing.
(iv) **Distribution** (j=4) includes FW at wholesale and retail level.
(v) **Consumption** (j=5). FW at this stage refer to waste during consumption at household and service industry level.

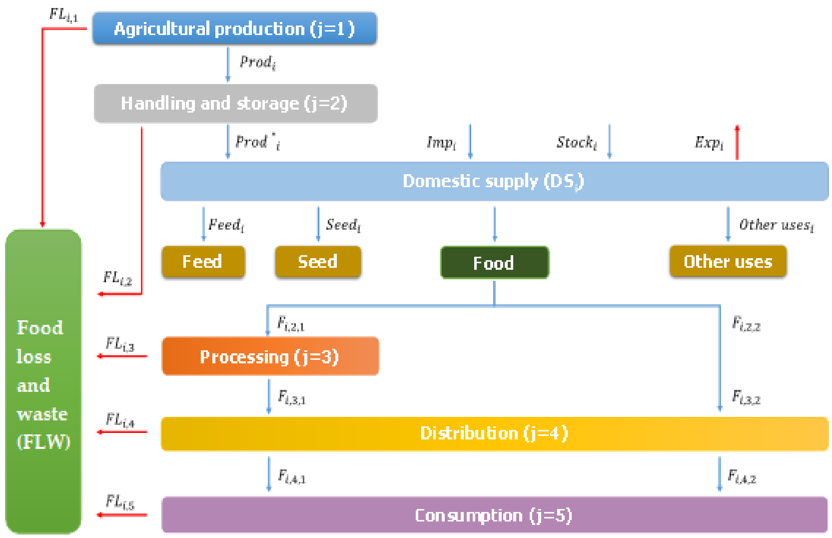

Figure 2.2 Material flow analysis model.

The most representative commodities products in terms of mass, nutritional and economic value are first selected for the specific country or region under study. Then, a food balance sheet (FBS) is constructed to determine the total domestic supply (DS). The FBS shows the patterns of a country's food supply during a specific period of time (Ju et al., 2017). There are different definitions for the term 'domestic supply'. According to the FAO (2001), it refers to the total amount of food available to be used in a spatial unit under study after production loss. Imports, exports and stock variation have been considered (FAO, 2001). Other definitions withdraw also postharvest losses from the total amount of food available (Kummu et al., 2012), as indicated in Equation 2.1:

$$DS_i = \sum supply\ elements_i = Prod_i + Imp_i + Stock_i - Exp_i - FLW_{i,2} \qquad [2.1]$$

Where $Prod_i$ refers to the country's food production in a specify year for food category *i*. For primary commodities, production relates to the total domestic production at the farm level for crops (excluding harvesting loss) and livestock (expressed in terms of carcass weight for meat items). For fish, it refers to the live-weight equivalent of the landings of the retained catch. Production of processed commodities relates to the total output leaving the manufacture level. Imp_i and Exp_i describe all movements of the commodity in question in (imports) and out (exports) of the country as derived from trade data statistics, including both raw and processed items. $Prod^*_i$ refers to the country's food production after postharvest loss ($FLW_{i,2}$) is considered.

Once the domestic supply is estimated, food available for human consumption is determined using Equation 2.2:

$$Food_i = DS_i - \sum utilisation\ elements_i = DS_i - (Feed_i + Seed_i + other\ uses_i) = F_{i,2,1} + F_{i,2,2} \qquad [2.2]$$

Where $Food_i$ represents all forms of the food category *i* available for human consumption after withdrawing the utilization elements feed, seed and other utilities from the domestic supply quantity (FAO, 2001). $Feed_i$ describes the amount of commodity used for animal feed. $Seed_i$ is the amount of commodity used for reproductive purposes, e.g. seed, planting, fish for bait. $Other\ uses_i$ refers to the quantities of commodities used for other non-food purposes, e.g. wheat for bio-energy production. $F_{i,2,1}$ and $F_{i,2,2}$ describe unprocessed food addressed to the processing stage and fresh utilized food directed to distribution, respectively. The volume of FLW for each commodity group is calculated differently depending on the FSC stage. For example, agricultural production loss is estimated as having occurred before the production volume is derived, while postharvest and storage losses calculated as a percentage of the reported production value. The rest of FLW are determined as a function of the food quantity entering the corresponding stage. Consequently, the total volume of FLW for each commodity group throughout the FSC is quantified using Equations 2.3 and 2.4:

$$FLW_i = \sum_{j=1}^{j=5} FLW_{i,j} = \left(\frac{\alpha_{i,1}}{1-\alpha_{i,1}} + \alpha_{i,2}\right) \cdot \beta_i Prod_i + \sum_{j=3}^{j=5} \sum_{k=1}^{k=2} \alpha_{i,j,k} \cdot F_{i,j-1,k} \qquad [2.3]$$

$$FLW_{i,j} = \sum_{k=1}^{k=2} F_{i,j-1,k} - F_{i,j,k} \qquad \forall j \in [2,5] \qquad [2.4]$$

Where $\alpha_{i,j,k}$ is the percentage of FLW generated in each *j* stage for food category *i;* subscript *k* refers to food utilized processed (k=1) or fresh (k=2); $F_{i,j,k}$ is the food available for human consumption of category *i* leaving the supply chain sector j and $\theta_{i,}$ is the allocation factor used to estimate the fraction of produced food that is allocated to human consumption.

Nutritional food loss and waste footprint (NFLWF)

The quantification of FLW have been recognized as a necessary step to identify how much, why and where FLW occur (Møller et al., 2014). On the other hand, improving FLW assessment methodologies has been remarked as crucial for overcoming the methodological weaknesses and to increase transparency (Chaboud, 2017). According to this and in line with the FAO definition of FLW, the starting hypothesis of this work is the conviction that future strategies to reduce FLW along the FSC must take into account not only the quantification but also the 'qualification' in both economic and nutritional terms. This will provide stakeholders with a range of at least three indicators (FLW in mass, in economic terms and in nutritional terms). Although decision-making process is in general straightforward when one option under study scores better than the rest in all indicators simultaneously, it becomes difficult otherwise (Cortés-Borda et al., 2013). The need of a single score is therefore posed in situations where trade-offs between indicators do not allow choosing one preferable solution among the alternatives or one improvement among possible ones. Single scores are one-dimensional representation of all indicators considered for a particular system (Islam et al., 2017). However, they represent an issue highly debated in the scientific community, mainly due to the fact that a certain bias is introduced due to the choice of aggregation methods, which may change the conclusions drawn for the study (Pizzol et al., 2016). It should be recognized that i) there is no scientific basis for reducing results to a single overall score or number and ii) aggregation shall not be used in studies intended to be used in comparative assertions intended to be disclosed to the public (García-Herrero et al., 2017). Despite this, single scores are frequently used in practice to identify important impact categories, understanding the meaning of results by comparing with more familiar references or solving trade-offs between results (Pizzol et al., 2016). This section presents the *NFLWF* to assess the efficiency of the food system along the FSC, encompassing the measure of the economic and nutritional intensity of the FLW. In order to provide significance to the results and help in the decision-making process, this indicator distinguishes between FLW from cradle to gate (FLW-ctog) and FLW from gate to grave (FLW-gtog) depending leading to two separate indexes: *Nutritional Food Loss Footprint (NFLF)* and *Nutritional Food Waste Footprint (NFWF)*, respectively. NFLF can be used to analyze infrastructural decisions in the earlier FSC stages, while the NFWF is aimed at creating awareness among consumers.

Figure 2.3 describes the methodology approach followed to estimate the *NFLFW*. First, the previously described MFA is conducted to quantify the FLW along the FSC. Then, economic and nutritional losses are assessed to qualify the efficiency of the FSC. Finally, the NFLWF and the potential for FLW reduction are determined.

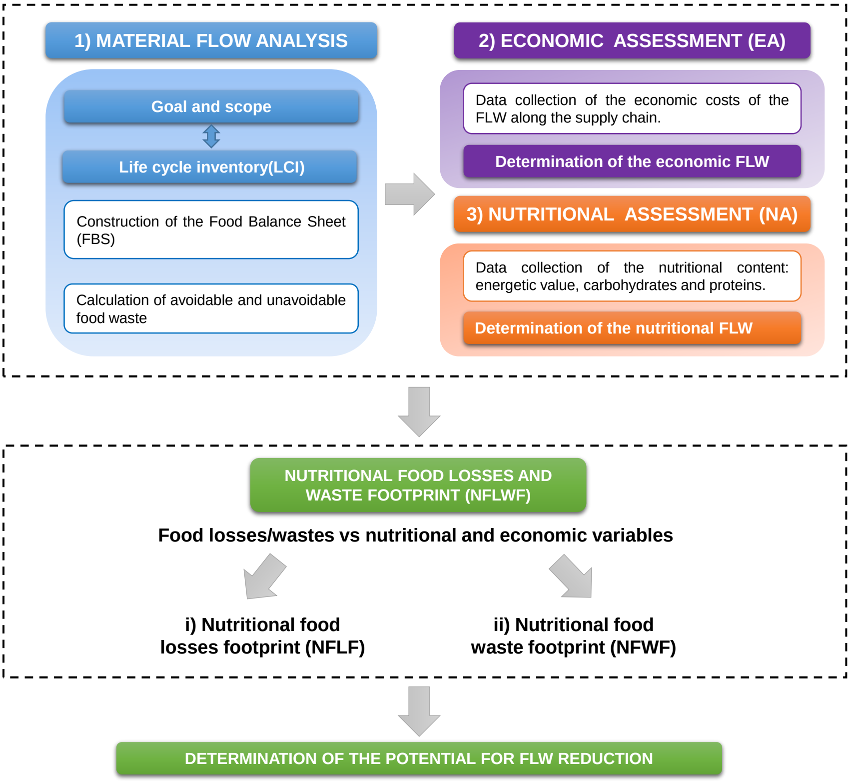

Figure 2.3 Methodological approach proposed for the determination of the Nutritional Food Loss and Waste Footprint (NFLF and NFWF).

To estimate the NFLWF, it is first necessary to determine the economic FLW (EFL) as described in Equation 2.5.

$$EFL_i = \sum_j EFL_{i,j} = \sum_j FLW_{i,j} V_{i,j} \quad [2.5]$$

Where $EFL_{i,j}$ represents the economic FLW of food category i in the supply stage j and $V_{i,j}$ their corresponding economic value. Furthermore, the nutritional FLW are also estimated (Equation 2.6).

$$NFLW_{i,l} = \sum_j NFLW_{i,j,l} = \sum_j FLW_{i,j} NC_{i,j,l} \quad [2.6]$$

Where $NFLW_{i,j,l}$ represents the FLW of food category i in the supply stage j for the nutritional descriptor (l=1, kcal; l=2, proteins, l=3, carbohydrates). $NC_{i,j,l}$ represents the nutritional content of food category i in supply stage j and nutritional descriptor l.

Determination of the NFLWF in the Spanish framework

Goal and Scope

The main goal of this work is to develop a standardized methodology to calculate the NFLWF to guide FLW strategies along the FSC in a specific region. A further goal of this study is to provide an analysis of the FSC efficiency in the Mediterranean region, in particular, in Spain. The functional unit selected for this work is defined as the supply of food for a Spanish citizen in 2015 in terms of food categories (Muñoz et al., 2010). The system boundaries comprise the entire supply chain, i.e. agricultural production, postharvest and storage, industrial processing, distribution (i.e. retail/wholesale) and consumption. The consumption stage was divided into household consumption and related extradomestic consumption, being the latter estimated at 22% of the total stage, based on the reported data from the Spanish Ministry of Agriculture, Fishery, Food and Environment (MAPAMA, 2012). This study does not consider the loss of food directed to animal feed, seed and other uses. FLW in other countries, resulting from the production of food imported for consumption in Spain, were included in the analysis. FLW resulting from the production of food for export was not included (Beretta et al., 2013).

A basket of products was selected based on the consumption data reported by MAPAMA (2015a). These food commodities were classified according to eleven categories following FAOSTAT classification: cereals, sugar, vegetable oils, vegetables, fruits, pulses, roots and tubers, dairy products, eggs, fish and seafood, meat and animal fat. Alcoholic beverages have been excluded from the analysis. These categories are assessed within the framework of four different diets: vegetarian, pescetarian, Mediterranean, and omnivorous diets. More data regarding the food commodities and diets considered are available in Table A1.1 in the Annexes.

Food balance sheet construction

An FBS is constructed following the methodology previously described. The domestic supply estimated includes the total production, but the assessment of the FLW only considers the fraction of the total production directed to human food. For cereals, production, stock, feed and seed values as well as postharvest loss were retrieved from the balance sheets built up by the Spanish Ministry (MAPAMA, 2017a). For sugar, production values are gathered from the European working document (EC, 2016). For vegetable oils, industrial production data were taken from the Statistics on industrial production and international trade (Eurostat, 2015e). Production and utilization elements of the dairy products category were also taken from the Spanish statistics of production and destination of milk in farms (MAPAMA, 2017b). For fish and seafood, total production is taken from Spanish statistics (MAPAMA, 2017c) and is the sum of the maritime catches and aquaculture (excluding hatcheries and nurseries) production. The share of utilization elements was taken from the aquaculture statistic by final destination and the same distribution for utilization of fish and seafood maritime catches was assumed. For the rest of categories, production values were mainly sourced from Eurostat (2015a, 2015b, 2015c, 2015d). International trade was mainly obtained from the Spanish database on international trade (DataComex, 2018). The relative percentages reported in FAOSTAT datasheets (FAO, 2013) were used to estimate the part of the total production intended for human consumption when no data were found for the year 2015, as well as the fractions addressed to the rest of utilization elements. Finally, national stock data were obtained from FAOSTAT database (FAO, 2013) and assumed similar to the food availability in 2013, which are the most updated data at present. To avoid double counting of ingredients, food categories were modelled at the level of ingredients. For example, for cereal based products such as breads and pastries only wheat was modelled; other ingredients such as sugar were allocated to other categories (Beretta, 2013, Meier and Christen, 2012). As a general rule, first-stage processing has been considered in most cases (i.e.

milling of cereals to produce flour). Second-stage processing has been taken into account in some cases (i.e. bread) and third-stage processing has not been considered (i.e. glucose). More information about the main sources of data information and the FBS construction are available in A1.2 and A1.3 of the Annexes.

Food loss and waste calculation

Percentage losses for agricultural production of crops were sourced from the Spanish report of MAPAMA (2013a). In this study, percentage losses are disaggregated into losses during cropping because of weather conditions and illnesses, harvesting, post-harvest and recycling into animal feed. For instance, data suggest that agricultural losses diminish on average from 20% to 7% when cropping is considered outside the system boundaries of the food losses definition. Consequently, data were adjusted to fit the definition of FL considered. Resulting percentages range from 7.9% for citrus fruits to 10.2% for grapes. These percentages are lower than those reported by the FAO for the European region (Gustavsson et al, 2013), estimated at 20% for fruits. Recent studies have shown lower agricultural losses for fruits, estimated at 9% in France (Redlingshöfer et al., 2017) and 10-14% for Nordic countries (Hartikainen et al., 2018). For cereals, a 6.6% of losses is estimated in agricultural production from MAPAMA (2013a). This value results higher than the 4.6% reported by FAO (Gustavsson et al., 2013) and the 2% estimated for France (Redlingshöfer et al., 2017), but agrees with the 14-4% range shown by Hartikainen et al. (2018). Spanish losses percentages were not found for meat, fish, dairy products and eggs production and thus the FAO values were used. As stated in Equation 2.3, allocation factors were used to determine the part of the agricultural product intended to human consumption and thus the part of the agricultural losses assigned to human consumption. These factors were calculated from the FBS in Table 2.1 and range from 20% for cereals to 83% for fruits. Vegetable oils, meat, fish and seafood, dairy products and eggs were assumed to be 100% intended to human consumption.Postharvest losses were estimated using FAOSTAT datasheets (FAO, 2013), excepting for cereals, for which national statistics data were used. Values from 0% to 10.8% were obtained for this stage, which are similar to those calculated by FAO for the European region. The largest difference is observed for fruits and vegetables, for which a 9% and 10.8% are calculated for Spain, while a 5% is reported for the European region (Gustavsson et al., 2013). Allocation factors were also used for estimating these FL, as previously explained.

Industrial losses were sourced from the Spanish report of MAPAMA (2013b) for cereals, roots, meat and dairy products categories. The rest of FLW percentages were sourced from Gustavsson et al. (2013). Hence, assumed losses for this stage are in the 0.2-14.7% range, being the lowest represented by the dairy industry and the largest by roots and tubers. Conversion factors were used to determine the assumed average proportion of the food utilized fresh and processed. Such factors were taken from the estimations of the FAO for Europe and range from 4% for fish and seafood to 40% for vegetables, fruits and pulses (Gustavsson et al., 2013). Finally, percentage of waste reported by FAO for Europe have been used to estimate the remaining FW at the distribution and consumption stages. The resulting FLW percentages are shown in Table 2.1 (and more detailed in Table A1.4).

Economic food loss and waste calculation

Prices at origin, wholesale and consumer level were obtained from the Spanish Ministry of Economy and Competitiveness (MINECO, 2015) and the MAPAMA (2015b) (see A1.5 in the Annexes). The same costs were assumed for FLW at agricultural production and postharvest stages. Regarding the processing stage, the economic values of production reported by Eurostat were used when consistent data where available. Otherwise, wholesale prices were used for the processing and distribution stages. It was assumed that the food service establishments and the related extradomestic services can buy their food for lower prices than private households. A 5% volume discount was considered (Beretta et al., 2013).

Nutritional food loss and waste calculation

Diet is an important determinant of human health (Tilman and Clark, 2014). Food commodities can be classified according to the diet where they are present: vegetarian, pescetarian, Mediterranean and omnivorous diets. The diets have different compositions. A vegetarian diet includes cereals, roots and tubers, sugar, vegetable oils, vegetables, fruits, pulses, dairy products and eggs. A pescetarian diet is a vegetarian diet that includes fish and seafood. A Mediterranean diet is similar to the pescetarian, but includes moderate amounts of meat. Omnivorous diets consider all food groups. In addition to the diet classification, food commodities can be characterized according to their nutritional content. Proteins, carbohydrates and caloric content of the food commodities were sourced from the Spanish Bedca database (2017) and are outlined in A1.6 in the Annexes.

Avoidable and unavoidable food loss and waste calculation

Although inedibility food content is the most usual criteria followed for determining unavoidable FLW, the boundary between edible and inedible food is often subjective. This is due to its related variability over time and among different countries and cultures (Chavoud and Daviron, 2017). In this work, the definition of Beretta et al. (2013) for unavoidable FLW and the methodology proposed by Kummu et al. (2012) are followed. In this sense, a minimum scenario is defined to quantify the potential for FLW reduction. This scenario assumes that for each FSC stage, the lowest loss percentages reported by Gustavsson et al. (2013) in any region, can also be achieved in Spain. The minimum FLW are then identified with the unavoidable FLW (see A1.7 in the Annexes).

Main assumptions and limitations of the study

This study assumes that there is no discrepancy between domestic supply and domestic utilization and, consequently, it is assumed that all goods sold and all food imported are consumed. The FLW generated in other countries owing to the production of food for importation to Spain is considered, assuming the FLW rates to be equal to those in Spain. The FLW rates are considered to be representative figures for each category, disregarding the differences among food items in the same category. In some cases, the FLW rates were taken from Gustavsson et al. (2013), which assumes that the FLW percentages are identical for all European countries. Consequently, the results in such cases do not reflect entirely country-specific differences concerning behavior and technologies (Bräutigam et al., 2014). Nutritional data available in databases serve at the description of edible parts of food. Despite this does not exactly fit with FLW composition, this study assumes that these data can be used to describe inedible parts of food as well. Similarly, to FLW in terms of mass, FLW in economic and nutritional terms have been estimated using a representative figure for each food category, estimated as the average value of the available data.

Table 2.1 Food loss and waste (FLW) percentages for each food category as a percentage of what enters in each supply chain stage. Unless stated otherwise, percentages are obtained from Gustavsson et al. (2013) for Europe region.

	Agricultural production	Postharvest handling and storage	Processing and packaging		Distribution		Consumption	
	$\alpha_{i,1}$	$\alpha_{i,2}$	$\alpha_{i,3,1}$	$\alpha_{i,3,2}$	$\alpha_{i,4,1}$	$\alpha_{i,4,2}$	$\alpha_{i,5,1}$	$\alpha_{i,5,2}$
Cereals (%)	6.6[1]	0.5	12.10[3]	1.80[3]	2.00	2.00	25.00	25.00
Roots and tubers (%)	8.3[1]	4.9[2]	14.70[3]		3.00	7.00	12.00	17.00
Sugar (%)	6.6[1]	0.00[2]	2.00		2.00	10.00	15.00	19.00
Vegetable oils (%)	5.9[1]	0.00[2]	5.00		1.00	1.00	4.00	4.00
Vegetables (%)	8.3[1]	9.0[2]	2.00		2.00	10.00	15.00	19.00
Fruits (%)	6.5[1]	10.8[2]	2.00		2.00	10.00	15.00	19.00
Pulses (%)	6.6[1]	8.2[2]	5.00		2.00	10.00	15.00	19.00
Meat (%)	3.20	0.00[2]	6.30[3]		4.00	4.00	11.00	11.00
Fish and seafood (%)	9.40	0.00[2]	6.00		5.00	9.00	10.00	11.00
Dairy products (%)	3.50	0.00[2]	0.2[3]		0.50	0.50	7.00	7.00
Eggs (%)	4.00	2.04[2]	0.50		2.00	2.00	8.00	8.00

(1) Extracted from MAPAMA (2013a) for Spain.

(2) Postharvest handling and storage percentages were estimated from the FAO Food Balance Sheets for Spain in 2013 (FAO, 2015) and assumed to be maintained for 2015.

(3) Extracted from MAPAMA (2013b) for Spain.

2.2.3 Results and discussion

Material flow analysis results

Results from the MFA are shown in the Sankey diagram of Figure 2.4. Since statistical production values do not account for the losses occurred during this stage, the FLW flow of this stage is generated before the production value is derived. In the agricultural production and postharvest stages, the allocated flow to FLW is distinguished from the resulting flow assigned to non-food uses. The net domestic supply after considering agricultural production and postharvest losses, imports, exports and stock variation is 78,656 Mton per year. From this, 31,353 Mton (40%) are used for animal feed and 6,832 Mton (9%) are employed for seed and other non-food uses, such as oil for oil production and wheat for bio-energy. The material balance also reveals that only 47% of the net domestic supply is addressed to human consumption. However, just 41% is finally ingested, while the rest is lost or waste.

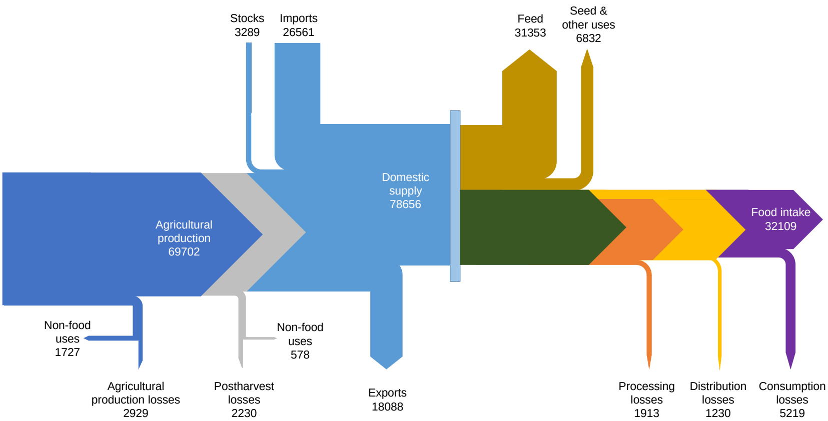

Figure 2.4 Sankey diagram for the Spanish agri-food system in 2015. All values shown in thousand tons.

Food loss and waste quantification

The FLW analysis reveals that vegetables and fruits are the food categories most affected by the inefficiencies in the FSC (Figure 2.5). Their FLW were estimated at 70 and 65 kg cap^{-1} yr^{-1}, respectively, which account for almost 60% of the total Spanish FLW. They are followed by cereals category, whose contribution to the total FLW is around 20%. Consequently, no significant difference is observed in food mass lost among the different diets studied, since the majority of the FLW are shared by fruits and vegetables, which are present in every diet. Household consumption is the main step contributing to FLW, amounting to 30% for the food categories under study. The quantity of food annually wasted in households was estimated at 88 kg per person. More than a third of this waste is due to fruits and vegetables, which are highly perishable. Secondi et al. (2015) suggested that FW in this stage is the result of multiple factors relating to various aspects rather than the outcome of a single behavior. The education level, sorting practices, the extent of urbanization and concern were some of the variables proved to be associated to individuals' behavior. Conversely, FW in the service sector results three times lower (24 kg cap−1 yr−1) than at households. After household consumption, agricultural production and postharvest stages are the second main hotspots for FLW (38%). This contribution is more significant for fruits and vegetables (57%), owing to climatic conditions, diseases and pests (MAPAMA, 2013a). On the other hand, inefficiencies in manual and technical harvesting, unsatisfied quality standards and mismatch between offer and demand cause fruits and vegetables losses in both harvest and postharvest.

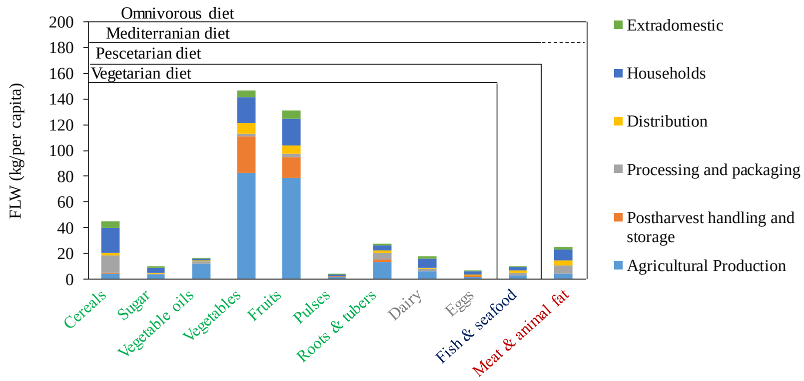

Figure 2.5 FLW of the different food categories throughout the supply chain. Values expressed in kilograms per capita.

According to Figure 2.6, the described pattern is reversed when the economic value of FLW is assessed. The category of meat and animal fat emerges as the largest contributor to economic wastage, representing a 39% (144 €·cap^{-1} yr^{-1}) of the total FLW. It is followed by far by fruits and vegetables categories, which share 15% and 14%, respectively. Therefore, it can be concluded that those diets including meat on the menu such as Mediterranean and omnivorous, involve higher economic FLW than those avoiding this category, such as vegetarian and pescetarian diets. Regarding the FSC stages, it can be observed that the closer to the consumer the FLW are generated, the more expensive they become. Consequently, household consumption is the main hotspot of economic FLW, accounting for nearly half of the total economic wastage. The analysis developed estimates that each Spanish citizen throw away around 184€ of food per year, which is below the European average estimated at ca. 195€ (Stenmarck et al., 2016). According to the Spanish Confederation of Consumer and User Cooperatives (HISPACOOP, 2013), half of this FLW could be avoided with an adequate purchasing and storage planning. Improper preparation, lack of awareness about the difference between expiration and preferential consumption dates and portion size acquired in the supermarkets are other reasons for FW generation in households. As opposed to household consumption, extradomestic services account for 13% of economic FLW. Regarding economic FLW-ctog, agricultural production and processing account both for 11% of economic FLW. Therefore, the results suggest that economic FLW at the beginning of the supply chain are not as significant as at the consumption stages. This could be the reason why no substantial improvement actions are being addressed to the early stages of the FSC.

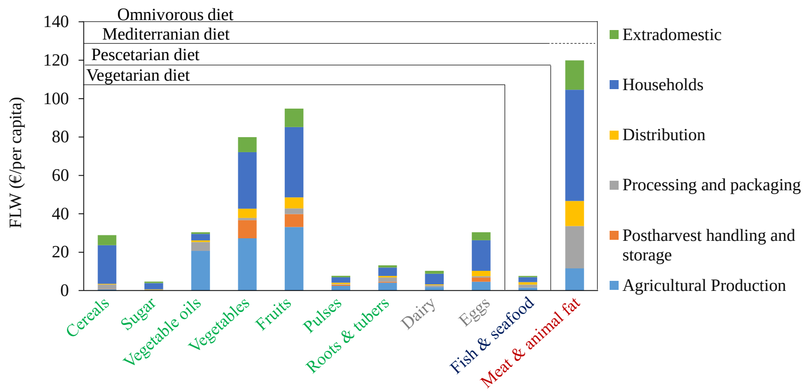

Figure 2.6 FLW of the different food categories throughout the supply chain. Values expressed in euros per capita.

Nutritional assessment of the food loss and waste

Figures 2.7, 2.8 and 2.9 compare the nutritional content of the FLW for the different food categories to their economic value. FL and FW are disaggregated to distinguish between producers' and consumers' decision-making. Three different indicators are assessed: i) energy content (kcal), ii) proteins and iii) carbohydrates. A rating letter is used to sort the different food categories according to the intensity of the nutritional-economic wastage. "A" is for the food categories with less nutritional-economic FLW intensity, while "C" is for those with higher intensity. For example, sugar category shows the best rating in terms of energy losses (Figure 2.7a). Conversely, its rating is deteriorated to "C", when the energy loss is assessed. On the other hand, the classification of a food category can vary among the different nutritional features. Such is the case of cereals category, which gets "C" for energy losses and "B" for protein and carbohydrate losses. To simplify the decision-making, the rating method scales from "AAA" to "CCC" to be finally translated into global "A" and global "C". This constitutes the NFLF and the NFWF indicators.

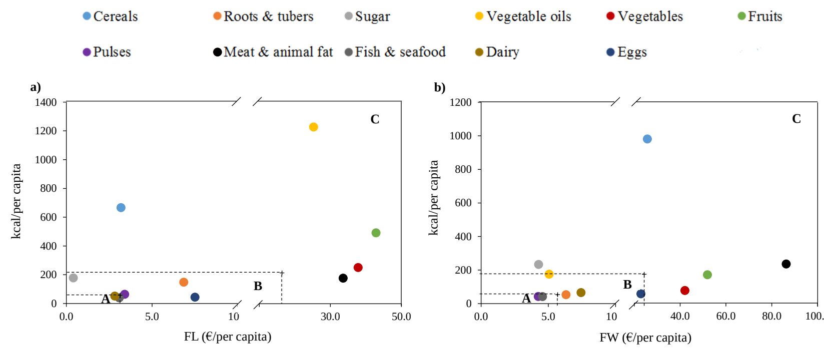

Figure 2.7 Energy content of a) food loss (FL) and b) food waste (FW) for the different food categories throughout the supply chain versus their related economic value. Values expressed in kcal per capita.

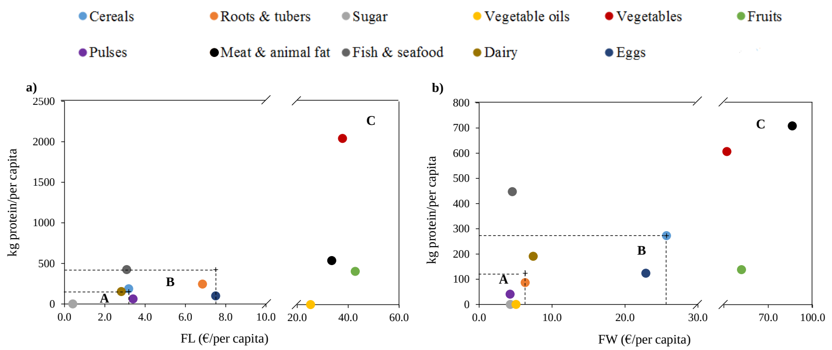

Figure 2.8 Protein composition of a) food loss and b) food waste for the different food categories throughout the supply chain versus their related economic value. Values expressed in kilograms of proteins per capita.

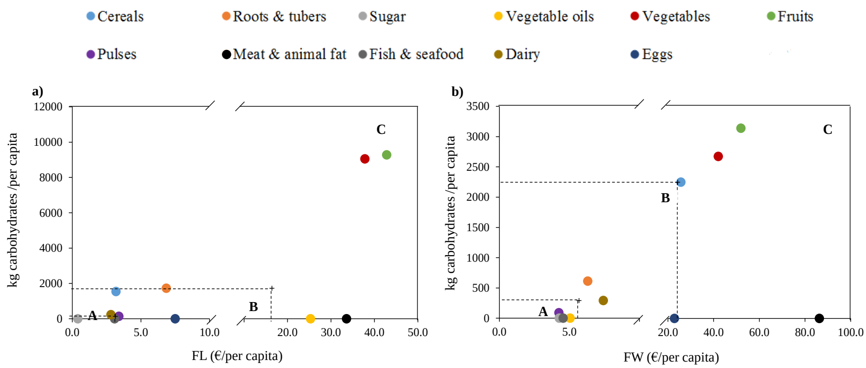

Figure 2.9 Carbohydrates composition of a) food loss and b) food waste for the different food categories throughout the supply chain versus their related economic value. Values expressed in kilograms of carbohydrates per capita.

As outlined in Figure 2.10, meat, fruits, vegetables and vegetable oils present the worst NFLWF (C), since the largest nutritional and economic losses at the beginning of the FSC are attributed to these commodities. As was previously observed, this is essentially due to the losses generated in agricultural production. Therefore, mitigation strategies should be focused on this stage for these categories. The exception is meat category, for which the largest economic and nutritional losses are produced in the processing and packaging stage. A better rating (B-) is observed for cereals, whose NFLWF-ctog is deteriorated owing to the energy losses. On the other hand, the best NFLWF-ctog is observed for dairy products (A), which show the largest nutritional-economic efficiency between agricultural production and distribution stages.

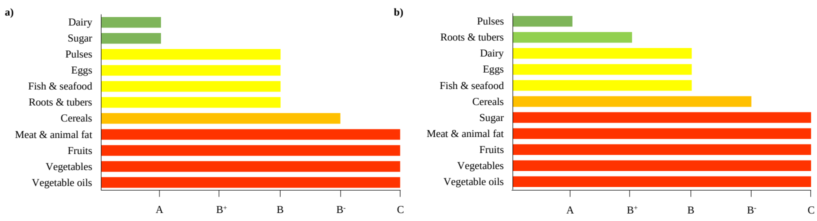

Figure 2.10 a) Nutritional Food Losses Footprint (NFLF) and b) Nutritional Food Waste Footprint (NFWF).

Regarding the distribution and consumption stages, the worst NFLWF is again observed for meat, fruits, vegetables and vegetable oils (Figure 2.10b). On the other hand, the classification is reversed for other categories such as dairy products and sugar. This is mainly due to the increase in the price of these commodities at consumption stage with regard to their price at origin, especially for sugary products. Conversely, pulses and roots and tubers categories improve their nutritional-economic efficiency, changing from B to A and B^+, respectively.

Determination of the potential for food loss and waste reduction

The results for the avoidable and unavoidable FLW are described in Figures 2.11 and 2.12. As shown, around a third of the FL generated from agricultural production to processing (FLW-ctog) could be prevented in comparison to the existing situation (Figure 2.11a). Results suggest that postharvest handling and storage is the stage where most improvements can be achieved, since this process is responsible for 55% of the avoidable FLW-ctog (Figure 2.11b). Conversely, the minimum efforts are required in agricultural production, since this stage only generates 10% of the avoidable losses. As shown in Figure 2.12a, cereals exhibit the highest potential for improvement in terms of FLW-ctog (68%), followed by pulses (59%). On the other hand, sugar and vegetable oils present the largest FSC efficiency from agricultural production to processing, since they exhibit the lowest potential percentages of reduction.

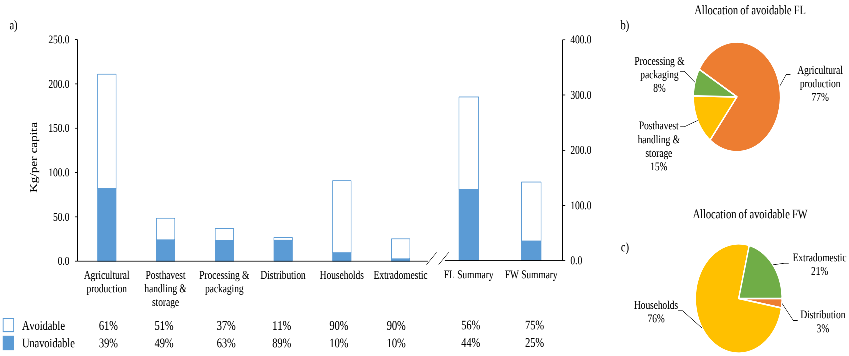

Figure 2.11 Results for the potential FLW reduction across the food supply chain. FL refers to agricultural production, postharvest and processing together. FW refers to distribution, households and extradomestic consumption. A: Contribution of the avoidable losses at each stage of the food supply chain. Results are expressed in both kg per capita and percentage over the stage. B: Allocation of avoidable food loss. C: Allocation of avoidable FW.

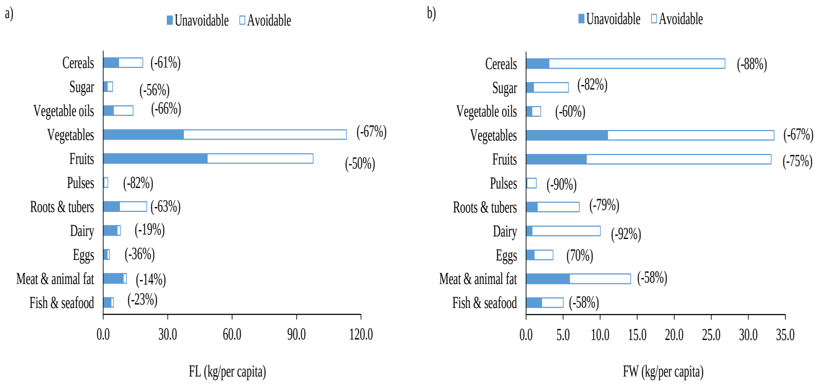

Figure 2.12 Results for the potential food loss (a) and food waste (b) reduction for the different food categories under study. Negative percentages represent the potential reduction that can be achieved for each food commodity owing to avoidable food loss and waste.

Furthermore, Figure 2.11a shows how the unavoidability of the losses increases as the food moves through the supply chain, increasing from agricultural production (8%) to consumption (89%). In terms of FLW-gtog, the majority of avoidable losses are produced in households (76%, Figure 2.11c). Extradomestic consumption and distribution stages are by contrast, much less contributing to FLW-gtog (21 and 3%, respectively). Therefore, the target of the European Parliament of halving FW by 2030 could be achieved if efforts are essentially addressed to consumers. Regarding food categories, dairy products emerges as the commodity with higher potential for improvement (92%, Figure 2.12b), followed by pulses (90%) and cereals (88%). Conversely, meat and fish are the categories less lost, showing both a 58% potential reduction. Regarding economic losses, the potential reduction percentages are similar to those described in Table 2.2.

Table 2.2 Results for the potential food loss (FL) and food waste (FW) reduction in economic and nutritional terms. Baseline scenario refers to Spain in 2015.

	FL		FW	
	Baseline	**Min. scenario**	**Baseline**	**Min. scenario**
€·cap^{-1}	103	78 (−24%)	266	64 (−76%)
kcal·cap^{-1}	211,784	131,658 (−38%)	239,572	49,083 (−80%)
Kg proteins·cap^{-1}	26	18 (−28%)	26	8 (−69%)
Kg carbohydrates·cap^{-1}	105	65 (−38%)	84	20 (−77%)

Results suggest that a 24% percentage of the economic FLW-ctog could be prevented, while 76% of the economic FLW-gtog could be saved. The largest potential for improvement lies in household consumption, where around 160€ per inhabitant and year could be saved. In nutritional terms, it can be remarked that around 451,000 kcal cap^{-1} yr^{-1} were lost or wasted in 2015. From this, more than 270,000 kcal cap^{-1} yr^{-1} are estimated to be avoidable, amounting to 1.26 10^{13} kcal. Assuming 2,100 kcal as the daily kilocalories needed for an average person to lead a healthy life (Kummu et al., 2012), this would have been enough to feed 16.4 million people in that year.

Strategies for food loss and waste management

Traditionally, waste management strategies have been defined according to the waste hierarchy, which establishes a set of priorities for reducing and dealing with waste generation. However, the waste hierarchy have been criticized for being primarily focused on delivering the best environmental option over social and economic factors. Furthermore, discarded food is a complex flow, for which specific guidelines are required. Some food recovery strategies have already been proposed, such as the Moerman ladder in the Netherlands (Waarts et al., 2011), the Food Recovery Hierarchy in the United States (USEPA, 2014), and the Food Waste Pyramid in the United Kingdom (Feeding the 5000, 2014). They all prioritize prevention, since the waste management options include downcycling and loss of the intended product (Eriksson et al., 2015).

The proposal of this section comprises a double pyramid, which combines the FLW management hierarchy to the NFLWF pyramid, as a graphical tool to communicate to Spanish producers (NFLFW-ctog) and consumers (NFLFW-gtog) which are the main efforts required and to which food categories should be addressed (Figure 2.13).

On the left, the classic upside-down pyramid that interprets and applies the waste hierarchy in the context of FLW, ranging the strategies from most to least favorable. The NFLWF pyramid, placed complementary to the former, shows the food categories with higher NFLWF on the top and those with greater nutritional-economic efficiency on the bottom.

As shown in Figure 2.13, two different levels are first distinguished in the FLW management pyramid based on Papargyropoulou et al. (2014) approach: food surplus and FLW. Surplus food is the edible food that is produced, manufactured, retailed or served but for various reasons is not sold to or consumed by the intended customer (Garrone et al., 2014). The management of food surplus has been highlighted as a critical element to mitigate food insecurity. Strategies associated to its management can be divided into prevention and re-use techniques. The most favorable option is prevention of food surplus and FLW. The former refers to reducing food surplus by not producing un-necessary food and building awareness regarding sustainable production and consumption. For FLW-ctog, prevention strategies include improving agricultural infrastructure, technological skills and more efficient storage, transport and distribution techniques. Sheahan and Barret (2017) criticize that most FLW reduction strategies are posed after harvest, although the compounding effects of pests and deterioration are accumulated before harvest. For FLW-gtog, such strategies should consider the improvement of food labelling, better consumer planning when shopping and preparing food, as well as technological improvements in packaging and improving shelf life for perishable foods. Once prevention via is depleted, donation can prevent food surplus from becoming lost. However, this strategy is essentially eligible for unsellable but not inedible food at supermarkets and post-harvest stage. Regarding the latter, Lee et al. (2017) remark the high uncertainty in both the supply of food (quantity and time) and the supply of labor (volunteer gleaners). It is necessary to develop a regulation framework and introduce strategies that boost and facilitate the donation.

The instant food is discarded from the human consumption supply chain and redirected to non-food uses, it becomes FLW. Then, recycling strategies are recommended. Recycling into animal feed is the most desirable and then, when no food can be made from FLW, the next best option is to process it into feedstock for industrial processes (e.g. bio-plastics). After recycling via is depleted, recovery strategies are recommended. Some examples are the production of fertilizer through composting, the production of biogas and digestate from AD or the recovery of energy from incineration. Finally, disposal would be the least desirable option.

Since the food biosecurity requirements increase the higher the level in the FLW hierarchy, Eriksson et al. (2015) states that, there is a decreasing likelihood that the whole FLW flow will be suitable for the same type of waste management. There is a need of subdividing the FLW stream, instead of treating it in its entirety. As results suggest, fruits, vegetables, vegetable oils and meat are the food categories with higher NFLWF, they require a greater emphasis. Based on the hierarchy previously described, they primarily would need a reduction in their production. This would avoid the destruction of fruits and vegetables, which is often carried out to prevent price falling when there is overproduction (Waarts et al., 2011). On the other hand, fruit and vegetable losses could be avoided by improving agriculture and harvesting techniques or revising marketing standards for fruits and vegetables to increase the sale of these products with deviant shapes, colors or sizes, which are edible but nowadays unsellable. Once prevention via is exhausted, recycling is the next option. As observed in Figure 2.13, feeding is the most desirable option. However, FLW from animal origin are a potential source of risks to public and animal health and their use is highly restricted (EC, 2009). For example, the use of meat loss in ruminants (cattle, goat and sheep) diets is banned in the EU because of concerns about Bovine Spongiform Encephalopathy (BSE), a disease that does not affect pigs, poultry, or fish (Salemdeeb et al., 2017). Therefore, animal FLW should be collected separately from those of vegetative origin. After industrial processing, some animal wastes can be valorized into pharmaceuticals and cosmetics or bio-based materials (Jayathilakan et al., 2012). These uses are essentially eligible for processing and distribution stages, since FLW generated in the consumption stage is generally of low quality. Otherwise, recovering strategies are the best option. Composting kills pathogens, converts nitrogen from unstable ammonia to stable organic forms, reduces the volume of waste and generates a fertilizer. AD is also a good choice for stabilization of organic waste owing to the production of biogas and digestate, which can also be applied restrictedly as fertilizer. Finally, landfilling of organic waste is illegal and then is the last favorable option. It should be highlighted that food categories placed at the bottom of the NFLWF pyramid do not necessarily imply landfilling strategies, but less influence on the efforts pursued.

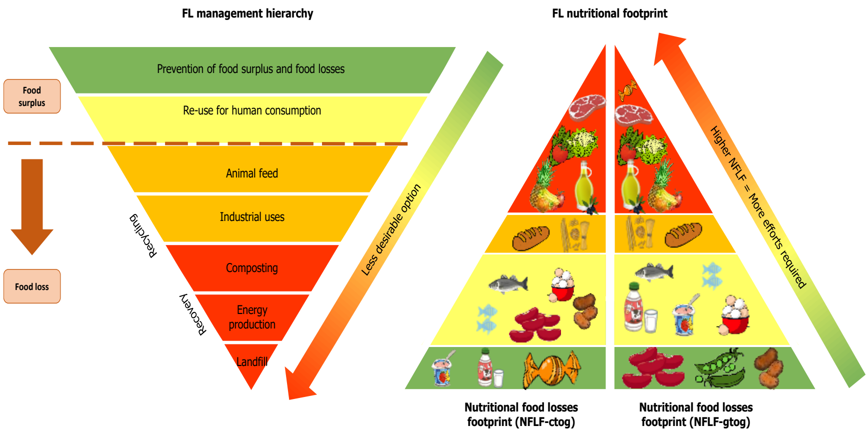

Figure 2.13 FLW management strategies.

Again, it must be remarked that this study follows the definition of the FAO for FLW (i.e. every discarded food initially intended for human consumption). It differs from FUSIONS' approach, which is defined by the final destination of discarded food, excluding food sent to animal feed, bio-material processing or other industrial uses from FLW. In such case, the pyramid should be adapted, to reflect that recycling into animal feed or some industrial uses are not part of FLW.

Discussion on sustainability of the Spanish agri-food system

Some food products, removed from the FSC, can be integrated into processing supply chains, which is a relevant market (Redlingshöfer et al., 2017). In this sense, one of the crucial issues when interpreting the results of this study is that discarded food going to a valorization step is not covered in the assessment due to the lack of data. However, it often represents a major flow (Scherhaufer et al., 2015). Despite the inclusion of such aspect would have not lower the amount of FLW, it could provide further insight regarding the sustainability of the agri-food system. FLW reduction does not in itself equate to a sustainable food system as there are many other aspects of food utilization that fall outside of the current FLW definitions. The problem of food co-products and by-products (FCB) generation is estimated to amount in Europe to 700 million tons annually. The AgroCycle project stated that a 10% rise in FLW recycling and valorization could have been achieved by 2020 by converting low-value FCB into highly valuable products (Ćosić et al., 2016a). For the meat category, FLW in this study are reported in carcass weight. Carcass weight represents near 60% of live cattle and pig weight, while the total FCB accounts for approximately 40% of the live weight. Around 203 and 1,876 thousand tons of slaughterhouse FCB were generated in Spain in 2015, for cattle and pig categories, respectively, considering the recycling of blood, fatty tissue, skin, tail, organs, bones and use for feed, which collectively account to 25% of the animal live weight. Some potential uses of these FCB are blood as an additive in human and animal diet, bone as livestock and poultry feed, production of food additives, cosmetic industry, offal (internal organs) as edible products, pharmaceutical industry or fertilizer. The remaining 15% is attributed to wastes, paunch, etc. (Ćosić et al., 2016a).

For the fruit category, pruning residues during harvest accounts for 6.5-30% of the total weight of harvested fruit, amounting to 2,322 thousand tons for apples, grapes, oranges, peach and small citrus fruits altogether in Spain for 2015. Pomace residues (peel, core, seed, calyx, stem) range from 22 to 60% of the processed fruits, estimated at 1,823 thousand tons for the same year (Ćosić et al., 2016b). Some valorization alternatives for these FCB comprise the recycling into feed, synthesis of biochemical such as bioethanol or fumaric acid. Larger FCB are obtained for cereals. During harvesting, potential FCB range from 1.35 to 4.93 kg of straw, stalks and cobs per kg of harvested cereal. During processing, bran and hull are the main products, ranging altogether from 11 to 47%. The total amount of FCB is estimated at 40 million tons in Spain, being maize, wheat and barley the main sources. Production of biomass, biofuels and feed are the main potential uses (Ćosić et al., 2016c).

Results indicate that the FLW element may be small in comparison to potential down-grade markets and thus co-products and by-products generation may have far more significant implication for system sustainability that the element that falls within current FLW definitions. This suggest that FLW definition should be precise not only by the origin of the discarded food but also by the destination.

Comparison to other studies

The first study on FLW considering the Spanish country was conducted by Monier et al. (2010). It estimated that around 7.7 million tons of food were wasted in Spain in 2006, excluding agricultural production and postharvest stages. This is well in line with the estimation done for 2015 excluding the same stages (8.3 million tons). Gustavsson et al. (2011) calculated that around a third of the total food production in terms of weight is lost or wasted across the FSC, amounting to 280-300 kg yr^{-1} cap^{-1} in Europe and North-America. These findings agree with this study, which estimates the generation of 291 kg FLW cap^{-1}, which represents a 20% of national production. Estimates of the FUSIONS project (Stenmarck et al., 2016) for EU-28 in each FSC stage are also well in line with the ones of this work: 33 vs 41 kg yr^{-1} cap^{-1} for processing, 21 vs 24 kg yr^{-1} cap^{-1} for food service and 92 vs 88 kg yr^{-1} cap^{-1} for households. The largest disagreement is observed in the first stage of the FSC, namely ‘primary production’ in FUSIONS project, whose estimation is 11 times lower than ours for agricultural production and postharvest stages together. The reason of such difference lies in the scope of FLW definition: FUSION’s definition does not consider as FLW the discarded food recycled into animal feed or valorization into bio-based materials and biochemical processing. Other studies have reported that agricultural production accounts for around 20-30% of the total FLW, which agrees with the resulting 22% obtained in our study (Porat et al., 2018).

Following the approach of Monier et al. (2010), the results of this study have been compared to the generation of animal and vegetal waste in Spain; despite animal and vegetal wastes may, in some instances, include some green wastes besides FLW (Eurostat, 2015f). Slurry and manure were excluded from the analysis. Per capita calculation used Eurostat data for 2014, since it is the year for which the most recent Eurostat data is available. In particular, it was found that for the sector ‘Manufacture of food products; beverages and tobacco products’, data agree with the presented results of this section for the processing stage: 37 vs. 37 kg per capita. Conversely, underestimations were found for the rest of stages (i.e. 21 and 19 kg per capita for agriculture and other sectors, respectively). Limitations in the reliability of Eurostat data were already remarked by Monier et al. (2010), due to the lack of clarity on the definition and methodology for collecting and calculating FLW and lack of information for some sectors.

Finally, Kummu et al. (2012) estimated that approximately half of the FSC losses and waste could be avoided compared to the current situation, lying the largest potential for improvement in agricultural production and consumptions stages as stated in this work. In particular, total nutritional losses along the FSC could be reduced by 63% in Europe, while a 60% potential improvement is estimated in this work.

2.2.4 Policy implications

FLW management has implications in several policy areas including sustainable resource management, climate change, energy, biodiversity, habitat protection, agriculture and soil protection (Secondi et al., 2015). For this reason, the estimation of the FLW mass quantity does not provide us with the complete picture of FLW implications. Current reduction policies refer to weight reduction targets, which does not distinguish among food categories and are only focused on the consumption stage. In this sense, this Section of the Thesis provides policymakers with an understandable methodology for estimating FLW not only in terms of weight, but also according to their nutritional and economic content. Hence, efforts can be addressed to critical food categories and supply stages. Moreover, the reduction potential of FLW for the different food categories is assessed, establishing a quantitative baseline for stakeholders to set targets and develop initiatives to minimize FLW. The findings of this section underline the possibility of setting individual reduction targets for each phase of the FSC. However, further research on food wastage causalities is required to assess negative externalities of FLW reduction, as it is understand that it is economically rational for producers and consumers to lose food as part of the costs are externalized. On the other hand, current waste policies do not establish clear strategies for prevention and management alternatives applicable to the case of food. This section presents a double pyramid for FLW management based not only on their "loss or waste" nature but also on their nutritional and economic value. The presented findings highlight the importance of establishing a legally FLW policy that applies the waste hierarchy in the context of FLW. Different prevention and management options should be clarified for the different food categories and supply stages. Finally, this work highlights the need of FLW separate collections and management, already recommended by the FUSIONS project.

2.2.5 Conclusions

This section estimates the FLW in Spain through the FSC in mass, economic and nutritional terms. Results suggest the importance of reducing FLW, as almost 20% of the national food production is lost along the FSC. A third of these losses are generated at household level, accounting vegetables and fruits together for a 30% of this amount. Each Spanish citizen is estimated to thrown away 88 kg of food per year, thus awareness campaigns and effort actions should be addressed to this stage. Agricultural production is also a major contributor to FLW, accounting for 22% of the total. Vegetables and fruits are again the main responsible of such loss and waste, estimated at 60%. When economic loss is assessed, the household level share half of the total losses, becoming meat the main contributing category. The findings of this work emphasize that economic losses at the beginning of the supply chain are not as significant as at the consumption stages. This can be the reason why no substantial improvement actions are being addressed to agricultural production and harvesting stages, especially for fruits and vegetables categories. The work also develops a methodology that balances both nutritional and economic variables to facilitate the decision-making process for the proper FLW management. A NFLWF is developed, which distinguishes between FLW from cradle to gate (NFLWF-ctog) and FLW from gate to grave (NFLWF-gtog). The former is addressed to identify those food categories which require efforts at the beginning of the supply chain, especially in production stage. The later refers to the consumption step and it can serve as a label to create awareness among consumers. In particular, the Spanish country, which is characterized by a Mediterranean diet, requires the development of strategies for fruits, vegetables oils and meat, which are the food categories with higher NFLWF regarding both FL (FLW-ctog) and FW (FLW-gtog). This work suggests that efforts should be addressed to food categories with higher NFLWF, for which specific-oriented strategies are required. Furthermore, it has been estimated the potential for FLW reduction through the quantification of avoidable and unavoidable FLW. The results suggest that around a third of the FLW generated from agricultural production to processing could be prevented (33%) compared to the existing situation. This percentage is increased to 75% for FW (FLW-gtog). In economic terms, it means that 160€ per citizen could be saved per year. Finally, it is estimated that around 16.4 million extra people could be fed if FLW are reduced. Future work will be addressed to the alignment of food measures at different stages of the supply chain in order to construct a loss-adjusted food balance sheet and derived specific loss factors. Moreover, the final destinations of discarded food would be explored to provide more insight into the FLW perspective. The approach here defined is applicable to other regions.

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2.3. Energy embedded in food loss and waste management and in the production of uneaten food: seeking a sustainable pathway

2.3.1 Introduction

Although energy and food have a well-known connection from the perspective of chemical energy contained in food products, the energy resources embedded for food production is less explored, and the available related information is scarce. Moreover, estimations are often limited to the first stages of production, without taking into account the fact that the FSC consists of several successive steps, and each one of them needs energy for its specific processes. In this line, once in Section 2.2 the assessment of the situation in Spain at national level was carried out in terms of mass, nutritional and economic loss, this section focuses on the analysis of the energy loss throughout the Spanish FSC. Therefore, it is firstly necessary to consider the fact, that with the FLW two types of energy are also lost: food energy loss (FEL), which is the nutritional energy of the FLW, and EEL, which is the primary energy invested in producing FLW. In addition, energy is required in the management of FLW after it has been disposed. Regarding to the latter, the efficiency in energy recovery through different management strategies, can vary considerably depending on the strategy and the FLW composition. In this sense, while most studies in the literature are focused on the efficiency assessment of the FSC, either from a mass (Corrado and Sala, 2018), an energy (Infante-Amate et al., 2014), or more than one point of view (Canning et al., 2010); this section intended to go further and contribute to the development of integrated FLW management strategies for energy-smart food systems. Thereby, the FAO proposal (2011) is followed, which focuses on the diversification of renewable energy sources through integrated food production systems, to ensure the access to energy and food security. Moreover, it is projected to follow two of the SDG for 2030 established by the United Nations Member States (UN, 2018): (i) SDG7, whose objective is to reach at least a 27% share of renewable energy consumption by 2030; and (ii) SDG12, which aims at halving FW at the retail and consumer level as well as reducing the FL along food production systems. On the other hand, the Circular Economy Package adopted by the EC in 2015 is guided by the EU waste hierarchy, which ranks waste management options according to their sustainability, and gives top priority to preventing and recycling of waste, placing the AD as an always-preferable option to incineration (EC, 2017). This ranking aims to identify the options most likely to deliver the best overall environmental outcome, and has been adopted worldwide as the principal waste management framework (Papargyopoulou et al., 2014). However, the waste hierarchy proposal considers FLW as a set without considering the different specific fractions or at which points along the FSC are they produced. Thus, this section aims also to develop the debate regarding the statement that the waste hierarchy is a too general proposal. This is in the same line as the thesis of Cristobal et al. (2018), who highlighted the fact, that when more criteria are considered along with the environmental one, other tools are needed for making the decision of which FLW management strategy is the most optimal. Finally, alternative FLW management strategies are presented. All it, under a circular economy concept based on a food waste-to-energy-to-food approach (as represented in Figure 2.14).

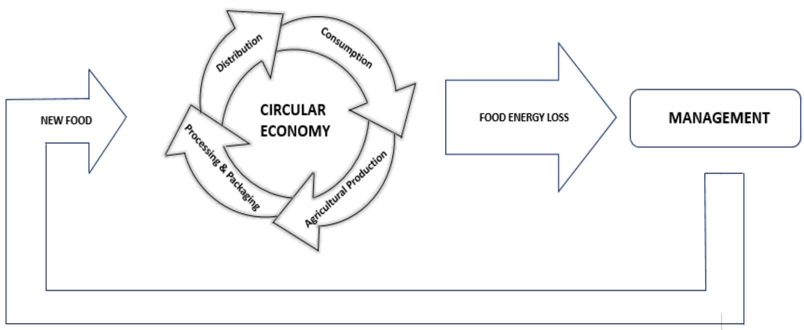

Figure 2.14 Conceptual diagram of the approach of this work, recovering energy from FLW with a circular economy approach.

2.3.2 Methodology

Goal and scope

The main goal of Section 2.3 is to develop a novel model to define alternative FLW management strategies under a circular economy concept based on a food waste-to-energy-to-food approach. For this objective, an empirical index so-called $EROI_{ce}$, is presented, which quantifies the amount of nutritional energy that is recovered from the FLW of each category of food under study, based on its treatment in three different scenarios: (i) landfill with biogas recovery (L), (ii) incineration with energy recovery (I) and (iii) anaerobic digestion and composting (AD&C). The results are expected to provide an interesting field for discussion about the best energy recovery strategy for the different fractions of FLW, trying to develop the path to less generic energy recovery proposals. In view of the results, it is expected to open a debate around a new framework of decentralized FLW collection strategies, instead, or as a complement to current centralized strategies.

Function, functional unit and system boundaries

This work is conducted following the international standards 14040 (2006) and 14044 (2006) from the ISO. The main function of the study is to determine what type of management strategy from the three different scenarios under study, is most appropriate for the FLW management of the categories analyzed, through the development of the $EROI_{ce}$ index. The functional unit is defined as the daily intake of an 11,493 kJ per capita and per day diet, by a Spanish citizen for 2015, which is obtained through an energy flow analysis. The system boundaries of this section include the steps of agricultural production, processing and packaging, distribution and consumption, being therefore realized from “cradle to consumer” (Figures 2.15 and A1.1). As this study relies heavily on the loss percentages reported by the Food and Agriculture Organization (Gustavsson et al., 2011), the definition of FLW is again based on their latest definition provided in 2014 (FAO, 2014).

Allocations

The scenarios under study are multi-outputs processes in which the management of FLW is the main function of the system and the production of electricity and compost are additional functions. The environmental burdens must be allocated among the different functions. To handle this problem the ISO 14040 establishes a specific allocation procedure in which system expansion is the first option. Regarding the landfill scenario, since electricity generation depends on the methane concentration in the landfill biogas, electricity recovered from FLW was allocated to the amount of total carbon available in the disposed organic residue. The incineration process was modelled based on Margallo et al. (2014), and in this sense, energy produced is calculated from the high heating value of each FLW fraction and the amount that is incinerated. In the AD&C scenario, methane is assumed to be combusted with a 25% efficiency of the low heating value of the biogas to generate electricity (Manfredi and Cristóbal, 2016). The delivering residue of the AD, i.e. digestate, is transferred to a composting plant for the production of compost. The compost is assumed to replace mineral fertilizer, with a substitution ratio of 20 kg N equivalent per ton of compost (Righi et al., 2013). Energy intensity for fertilizer production as total N is obtained from Thinkstep's Database (2017).

Life cycle inventory

For developing the energy flow analysis, data from different sources have been reviewed: the Department of Agriculture and Fishery, Food and Environment (MAPAMA, 2015), the Spanish Institute for the Diversification and Saving of Energy (IDAE, 2015), the Spanish Association of Plastics Industry (ANAIP, 2015), the Spanish Association of Pulp, Paper and Cardboard Manufacturers (2018), a magazine specialized in informing about the life cycle of packaging (INFOPACK, 2018), and the Foreign Trade Database (DataComex, 2018). Data for 48 representative commodities were sourced from the consumption database of the Spanish Department of Agriculture and Fishery, Food and Environment (MAPAMA, 2015). Items were grouped into 11 food categories (eggs, meat, fish and seafood, dairy products, cereals, sweets, pulses, vegetable oils, vegetables, fruits and roots), based on Section 2.2. It has been used several mass-to-energy conversion factors from different sources (Table A1.8 in the Annexes). All the results of the primary energy demand (PED), EEL and FEL by each food category under study, and on each FSC stage, can be consulted in Tables A1.9 and A1.10 of the Annexes. Nutritional data for the EROI and the ER estimation were obtained from the Bedca Database (2018) and can be consulted in Table A1.6 of the Annexes. Food products or ingredients not available in that database were sourced from the National Nutrient Database for Standard Reference of the United States Department of Agriculture (USDA, 2018). In practice, it has been assumed that the nutritional energy does not vary across the supply chain owing to the lack of data. The allocation, conversion and FLW factors used (Tables A1.11 and A1.12), are based on Gustavsson et al. (2013). The exception were some products, such as apples and bananas, for which specific FLW factors were available in Vinyes et al. (2017) and Roibás et al. (2016).

Assessment of food loss and waste management scenarios

Based on Laso et al. (2018), the electricity recovered in all the scenarios is assumed to be 100% sent to the grid, displacing electricity from the average electricity mix in Spain, and used for producing new food (Figure 2.15). This value could be lower if energy losses and its use for other purposes are considered. The analysis of these aspects would correspond to a consequential LCA, which could be analyzed in future works.

Scenario 1: landfill with biogas recovery (L). This scenario describes landfilling of FLW including biogas recovery. The landfill is composed of biogas and leachate treatment and deposition. The sealing materials (clay, mineral coating, and PE film) and diesel for the compactor is included. Leachate treatment includes active carbon and flocculation/precipitation processing. This scenario has been modelled based on the averages of municipal household FLW on landfill process from Thinkstep's Database (2017) for Spain, Portugal and Greece. According to the model, a 17% of the biogas naturally released from landfill is assumed to be collected, treated and burnt in order to produce electricity. The remaining biogas is flared (21%) and released to the atmosphere (62%). A rate of 50% transpiration/run off and a 100 years lifetime for the landfill are considered. Additionally, a net electricity generation of 0.0942 MJ per ton of municipal solid FLW is assumed (2017).

Scenario 2: incineration with energy recovery (I). The considered incineration plant, based on Margallo et al. (2014), is composed of one incineration line with a capacity of 12.0 t/h. The combustion is conducted in a roller grate system reaching 1,025°C. Flue gases are treated by means of a selective non-catalytic reduction system (for NOx), bag filter (dust, dioxins, etc.) and semidry scrubbers (acid gases). The main solid residues are fly and bottom ashes. The latter is subjected to magnetic separation to recover the ferrous materials. The inert materials are assumed to be landfilled close to the incineration plant. Fly ashes, classified as hazardous material, are stabilized and sent to an inert landfill. Energy produced in combustion is transferred to flue gases for energy generation. Energy produced is calculated from the high heating value of each FLW fraction and the incinerated amount. High heating values are obtained from the Thinkstep´s Database (2017). For example, average values of 4,832, 14,758 and 4,179 kJ/kg have been obtained for fish and seafood, cereals and vegetables.

Scenario 3: anaerobic digestion and composting (AD&C). This scenario considers the combination of AD&C of the solid fraction of digested matter, and is modelled using the life cycle inventory reported by Righi et al. (2013). The AD plant consists of a continuous two-steps process, where the first stage is a high-solid plug-flow reactor operating at thermophilic temperature and the second a completely stirred tank reactor at mesophilic temperature. The total retention time of substrates is about 100 days. The main product of AD is biogas, with an assumed 60% methane content. After it, methane is combusted in an engine to produce electricity. The delivering FLW of the AD, i.e. digestate, is transferred to a composting plant for the production of compost. The potential production of methane for each food category is calculated using the procedure reported by Eriksson et al. (2015), according to which the theoretical methane production is estimated as described in Equation 2.7:

$$Nm^3{}_{CH_{4,i}} = DS_i \cdot VS_i \cdot F_i \qquad [2.7]$$

where $Nm^3CH_{4,i}$ is the theoretical methane production of food category *i*; DS_i is the dry matter content; VS_i is the percentage of volatile solids in food category *i* expressed in dry matter terms; F_i is an specific production factor of methane expressed in $Nm^3CH_{4,i}$ per ton of volatile solids. These values are sourced from Carlsson and Uldal (2009).

Material and energy flow analysis

A material flow analysis quantifies the mass/resources flow, loss in a system, and facilitates in data reconciliation in a well-defined space and time (Padeyanda et al., 2016). As seen in Equation 2.8, the material flow analysis considers the FLW occurring along the supply chain as follows:

$$FLW_{i,j} = \frac{F_{i,1} \cdot \alpha_{i,j}}{\prod_{j=1}^{j} 1-\alpha_{i,j}} \qquad [2.8]$$

where $F_{i,j}$ is the food available for human consumption of category *i* leaving the supply chain sector *j* (*j* = 1 agricultural production, *j* = 2 processing and packaging, *j* = 3 distribution, *j* = 4 consumption). $\alpha_{i,j}$, is the percentage of FLW generated on each stage *j* for food category *i*. $F_{i,1}$ describes the daily intake of food category *i* for a 11,493 kJ per capita per day diet (Table 2.3). For this study, the MFA developed in Section 2.2, has been used as a reference. The energy flow analysis was developed through the combination of the MFA and the calculated PED for each food category along the supply chain.

Energy impact assessment

In this work, it has been introduced as energy impact assessment the $EROI_{ce}$ index in order to quantify the amount of nutritional energy that is recovered from the FLW of each category of food under study. The $EROI_{ce}$ index is based on a food waste-to-energy-to-food approach, assuming that the energy that is recovered from FLW is reintroduced into the FSC in form of food (Figure 2.15).

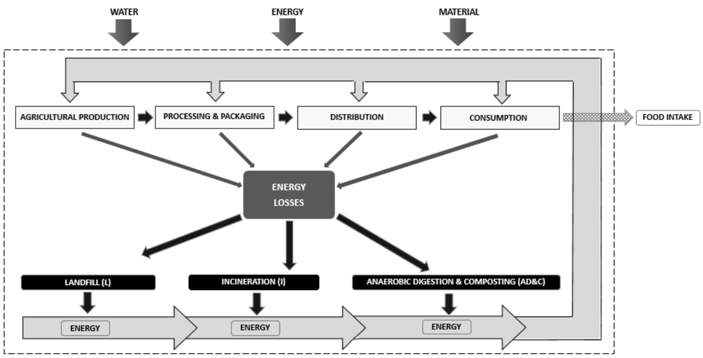

Figure 2.15 System boundaries, including the outline of the different considered scenarios.

For its development, the proposed methodology (Figure 2.16) firstly develops an energy flow analysis through determining the PED of each of the four stages in which the FSC is divided (agricultural production, processing and packaging, distribution and consumption), as seen in Equation 2.9:

$$PED_{i,j} = W_{i,j} \cdot AP_{i,j} \qquad [2.9]$$

where $W_{i,j}$ is the weighted average of energy intensity by mass of each category *i,* on each supply chain stage under study *j* (*j* = 1 agricultural production, *j* = 2 processing and packaging, *j* = 3 distribution, *j* = 4 consumption), in kJ/kg. APi, is the annual production of each category *i*, on each stage under study *j*, in kg.

Secondly, the EEL is computed, which means, the primary energy that was used to produce the food that is loss. EEL is calculated as stated in Equation 2.10:

$$EEL_{i,j} = \sum_{j=1}^{i}\left(PED_{i,j} \cdot \alpha_{i,j} - PED_{i,j-1} \cdot \alpha_{i,j-1}\right) \qquad [2.10]$$

To calculate it, the sum of the PED_i, multiplied by their respective percentages of loss $\alpha_{i,}$ is performed. From the second stage, these results are subtracted from the previous stage multiplied by their respective previous loss percentages $\alpha_{i,-1}$.

Once these data have been obtained, the FEL of each food category *i* under study is calculated. Following the Food and Agriculture Organization concept for FLW (FAO, 2014), FEL can be defined, as the amount of chemical energy contained in food and initially addressed to human consumption that, for any reason is not destined to its main purpose. It has been estimated according to Equation 2.11:

$$FEL_{i,j} = \left[\left(Prod_{i,j} \cdot F\right) \cdot NE_i\right] \cdot \alpha_{i,j} - \left[\left(Prod_{i,j-1} \cdot F\right) \cdot NE_i\right] \cdot \alpha_{i,j-1} \qquad [2.11]$$

where $Prod_{i,j}$ is the production of each category of food, which is multiplied by F, which are the factors of allocation and conversion presented by Gustavsson et al. (2013) to represent the amount of food that is used for human consumption and that is considered edible. These values are firstly multiplied by the nutritional energy, and next by the percentages of losses considered in the literature $\alpha_{i,j}$. From the second stage, the previously lost amount is subtracted, multiplied by the conversion factor of the previous stage $\alpha_{i,-1}$. Then, it has been calculated the EROI of each food category under study *i*, and each step *j*. EROI is the estimation of the quantity of energy delivered by a production technology relative to the quantity of energy invested (Pelletier et al., 2011). Although it was initially devised to the assessment of energy systems, the concept has been adapted (Equation 2.12) to quantify ratios of food energy output relative to food production energy inputs. This ratio can be estimated as follows:

$$EROI_i = \frac{NE_i}{PED_i} \qquad [2.12]$$

where NE_i, is the nutritional energy contained in each food category *i*, and PED_i is the primary energy demand for the production of each category *i.* Finally, the $EROI_{ce}$ is calculated. For it, the electricity recovered from the management of FLW is transformed into its equivalent amount of primary energy, and assumed to be redirected to the production of food. As shown in Equation 2.13, this index consist in the division between the nutritional energy $NE_{fw,i}$ obtained from the transformation into nutritional energy of the primary energy that is recovered through each FLW management strategy, and each FLW fraction of a specific food category; between the primary energy demand $PED_{fw,i}$ that was used in the management of FLW.

$$EROI_{ce} = \frac{NE_{fw,i}}{PED_{fw,i}} \qquad [2.13]$$

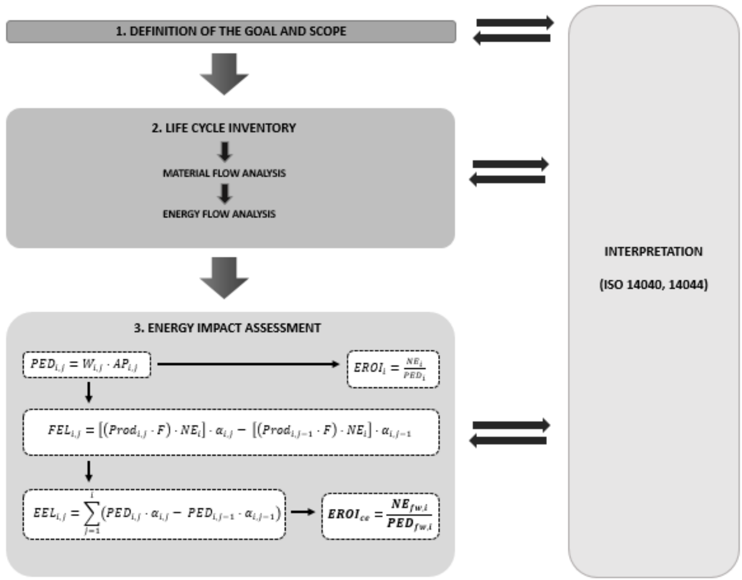

Figure 2.16 Methodology of the study.

2.3.3 Results

Energy flow analysis

Results from the energy flow analysis are shown in the Sankey diagram of Figure 2.17. The diagram represents the inputs and outputs of primary energy along the entire chain, using the reference unit (kJ day^{-1} cap^{-1}).

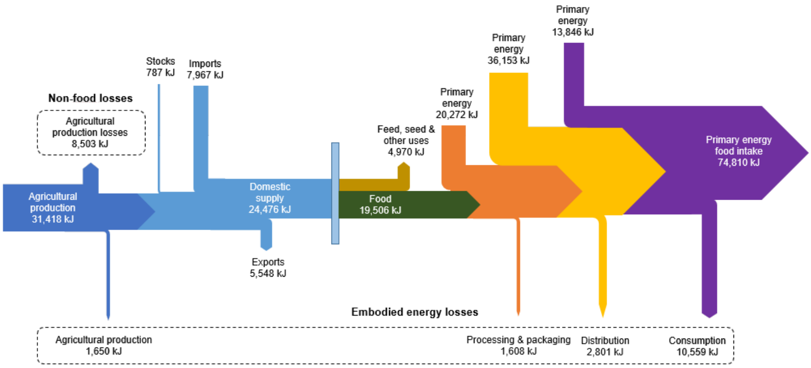

Figure 2.17 Sankey diagram for primary energy demand of the different food categories throughout the food supply chain. Values expressed in kilojoules per capita per day.

By calculating the primary energy balance until the end of the chain (99,926 kJ) which is need to produce the 11,493 kJ day^{-1} cap^{-1} of nutritional energy provided to consumer on average by each Spanish citizen; it is suggest that in the Spanish FSC, 8.7 kJ of primary energy is needed to produce 1 kJ of nutritional energy. In the agricultural production stage, the allocated flow to FLW is distinguished from the resulting flow assigned to non-food uses. The net domestic supply after considering agricultural production, imports, exports and stock variation is 24,476 kJ day^{-1} cap^{-1}. From this, 4,970 kJ day^{-1} cap^{-1} (20%) are invested in producing animal feed, seed and other non-food uses such as oil and wheat for bio-energy. The other 19,506 kJ day^{-1} cap^{-1} of the primary energy (80%) are used for food for human consumption. In this diagram, it is highlighted the fact that the stages with a higher PED are distribution (which in addition to distribution places, also includes national and international import transportation, as well as consumer transport to go to the markets) and agricultural production, followed by the stage of processing and packaging. These results could reinforce the thesis that the more local, seasonal and unprocessed the consumption, the lower expenditure of energy in transport and distribution. It is, however, important to note that a lower energy expenditure in transport and distribution does not necessarily mean a lower total energy expenditure in food production. There are a number of other factors that should be analyzed in future works in this field, as for example, the use of agrochemicals or tillage machinery.

When analyzing the food categories studied, it is observed that the ones requiring the highest PED for their production are meat, vegetables, fish and seafood and cereals, respectively (Table 2.3). Of the four categories, meat is the one with the highest PED (28,002 kJ day^{-1} cap^{-1}), doubling the value of the other three, and representing alone the 28% of the PED for all categories. These results could reinforce the thesis of the need to reduce the consumption of meat due to the energy costs that its production requires, as stated by Popkin (2009) and Laso et al. (2018). In addition, if the values for fish and seafood, eggs and dairy products categories are added to meat, more than half of the total PED comes from the production of food of animal origin (56,901 kJ day^{-1} cap^{-1}). In contrast, some categories, especially sweets and roots, have very low values.

Table 2.3 Primary energy demand, nutritional energy provided to consumer and energy return on investment. Values expressed in kilojoules per capita per day and percentage.

	PED (kJ $cap^{-}day^{-1}$)	Energy provided to consumer (kJ cap^{-1} day^{-1})	EROI (%)
Eggs	5,426	574	10.6
Meat	28,002	1,901	6.8
Fish and seafood	16,243	209	1.3
Dairy products	7,230	938	13.0
Cereals	13,922	3,827	27.5
Sweets	799	490	61.3
Pulses	2,511	226	9.0
Vegetable Oils	3,674	2,202	60.0
Vegetables	16,894	268	1.6
Fruits	3,535	540	15.3
Roots	1,691	318	18.8
Total	99,926	11,493	11.5

Regarding the values of EROI, sweets (61.3%) and vegetable oils (60.0%) are the food categories with the largest EROI, which indicates that these categories are the most efficient, although not necessarily the healthiest. It must be remarked that this work only assesses nutritional content in terms of energy; other nutritional features are not studied. They are followed by cereals and roots, with 27.5% and 18.8% EROI ratios, respectively. On the opposite side, fish and seafood, vegetables, meat and pulses have the lowest EROI, which indicates a very low energy efficiency in its production process. This agrees with results in the literature (Pimentel and Pimentel, 2008), which state that animal and animal derived food products consume large amounts of energy resources. Likewise, they reinforce the thesis of Popkin (2009) and Laso et al. (2018) on the environmental benefits of eating less meat and fish, since there is a huge potential for PED reduction.

Energy food losses quantification

The energy flow analysis reveals that in terms of EEL, which means the primary energy invested in producing FLW, meat, cereals, vegetables and fish and seafood are, respectively, the categories with the highest EEL values. Accordingly, they are the food categories most affected by the energetic inefficiencies in the FSC. Their EEL were estimated at 4,027, 3,259, 3,143 and 2,650 kJ day^{-1} cap^{-1}, respectively, which together accounts for almost 84% of the total Spanish EEL (Table 2.4).

In addition, once again, if the four categories of products of animal origin are added, it is highlighted the fact that around 50% of the total EEL is due to these products. In contrast, the categories with the lowest EEL values are sweets and vegetable oils, which represents values 20 times lower than the category with a higher value (meat). If the EEL is analyzed in the different stages, it can be clearly perceived that the stage of consumption is the one in which the highest EEL is produced, representing more than 66% of the total in the whole FSC (Figure 2.18). The total sum of the EEL values obtained, were around 17% of the total PED in the entire FSC.

In terms of the FEL, the categories of cereals, vegetable oils and meat, represent the highest values (Table 2.4). As this sequence coincides with the results of the energy provided to consumer (Table 2.3), these high values could be due to the high percentage of the European diet, which is based on cereals, vegetable oils and meat. On the other side, the categories with the lowest FEL are fish and seafood, pulses and eggs. This sequence agrees again with the results of the energy provided to consumer (Table 2.3), with the exception of eggs. Thus, the low values of FEL could be also related to the European diet, although other factors not analyzed in this work could influence them. Regarding the different stages of the FSC, the results show that the stage of consumption is the one with the highest values (Figure 2.18). Moreover, agricultural production plus processing and packaging together would be the part of the FSC with the highest FEL. The distribution stage, despite being the one that requires the most PED, is at the same time the one that clearly generates less FEL (7.4%). When it comes to recover energy from FLW, the qualitative and quantitative composition of FLW is essential, as stated in Section 2.2, and in this sense, from a quantitative point of view, these results suggest that the largest amount of FEL from which to recover energy occurs at the beginning and end of the FSC, being 1,130 and 1,290 kJ day^{-1} cap^{-1} the FEL in the stages of agricultural production and processing and packaging, and 2,349 kJ day^{-1} cap^{-1} in the stage of consumption. The total results of the FEL highlighted that approximately 5,154 kJ day^{-1} cap^{-1} are thrown away, which means that from a FEL point of view, for the consumption of two to three persons in Spain, one more person could eat.

Table 2.4 Primary energy demand, nutritional energy provided to consumer and energy return on investment. Values expressed in kilojoules per capita per day and percentage.

	FEL		**EEL**	
	kJ cap^{-1} day^{-1}	%	kJ cap^{-1} day^{-1}	%
Eggs	113	2	521	3
Meat	553	11	4,027	26
Fish and seafood	80	2	2,650	17
Dairy products	126	3	510	4
Cereals	2,386	46	3,259	21
Sweets	398	8	159	1
Pulses	96	2	421	3
Vegetable oils	687	13	233	2
Vegetables	176	3	3,143	20
Fruits	381	7	661	4
Roots	155	3	331	2
Total	5,151	100	15,915	100

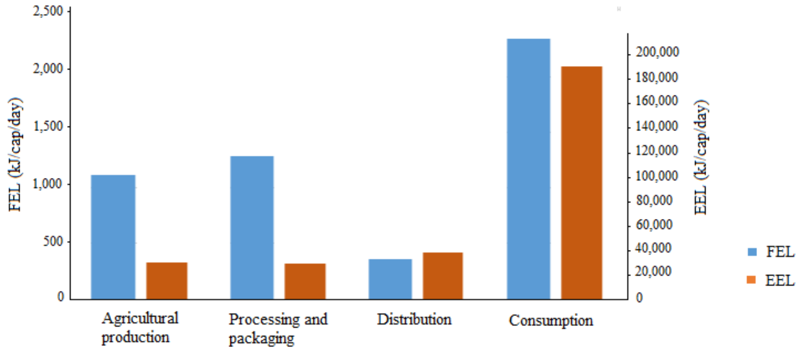

Figure 2.18 Food energy loss (FEL) and embodied energy loss (EEL) by stage of the food supply chain. Values expressed in kilojoules per capita per day (left and right ordinate axis).

Nutritional assessment of the energy loss

The food categories under study have been classified according to four different diets: vegetarian, pescetarian, Mediterranean and omnivorous. As explained in Section 2.2, a vegetarian diet includes cereals, roots and tubers, sweets, vegetable oils, vegetables, fruits, pulses, dairy products and eggs. A pescetarian diet is a vegetarian diet that includes fish and seafood. A Mediterranean diet is similar to the pescetarian, but includes moderate amounts of meat. Omnivorous diets consider all food groups.

Figures 2.19 and 2.20 represent the values obtained from FEL (kJ day^{-1} cap^{-1}) and EEL (kJ day^{-1} cap^{-1}), respectively, for the different food categories (abscissa axis) and the different stages (different colors in each column), being the numerical values signified on the ordinate axis.

If the FEL values for each category and stage of the FSC are related, it is clear that the category of cereals is the most wasteful one. From a quantitative point of view, it suggests that cereals should be the main category for placing the focus when developing FLW management strategies. Moreover, regarding the results, the change of the diet would not imply a significant change in terms of FEL, as can be seen in Figure 2.19.

On the other hand, Figure 2.20 displays the EEL values for each category and stage of the FSC. From the figure, it is observed that the type of diet does have a clear influence. The meat category presents the largest EEL values, followed closely by cereals, vegetables and fish and seafood, respectively. In terms of EEL, the vegetarian diet appears to be the one with the highest amount of primary energy saves, followed by the pescetarian diet. The consumption of meat in the Mediterranean and omnivorous diets supposes a significant increase of EEL.

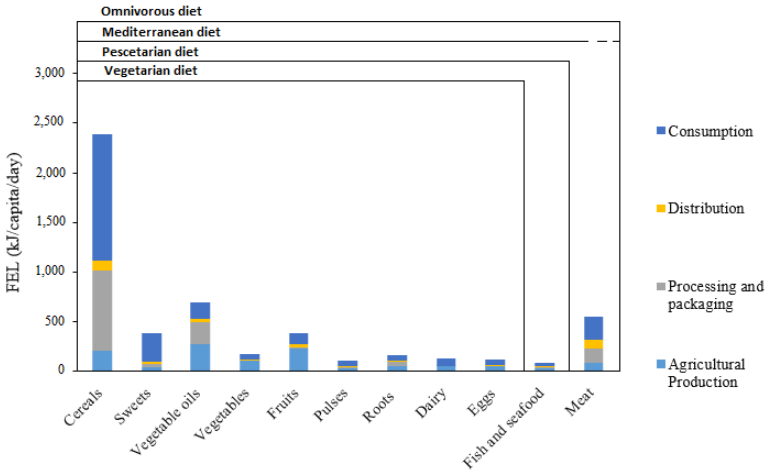

Figure 2.19 Food energy loss (FEL) of the different food categories throughout the supply chain. Values expressed in kilojoules per capita per day.

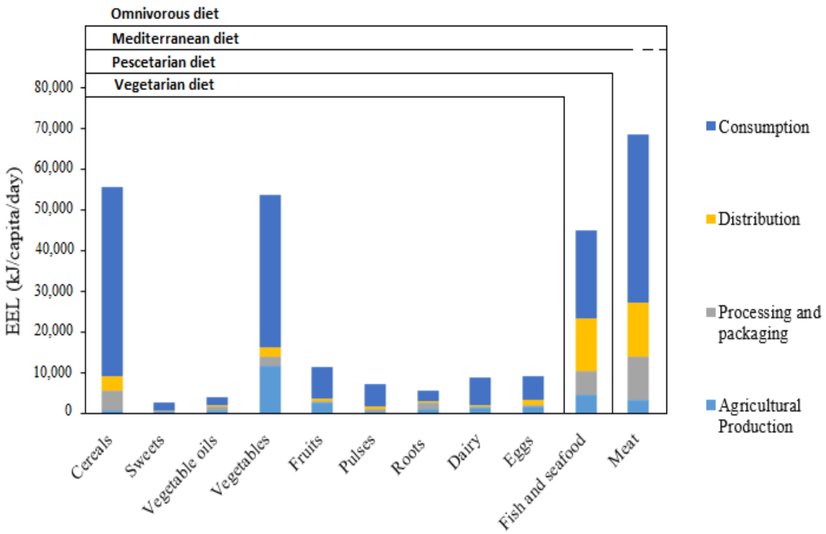

Figure 2.20 Embodied energy loss (EEL) of the different food categories throughout the supply chain. Values expressed in kilojoules per capita per day.

Taking into account an overall results overview, it is suggested that due to the higher mass losses of cereals, their value stands out against the others. However, in case of meat and fish and seafood, when analyzing the energy used in its production, those categories have a very high PED to produce low levels of food.

Energy return on investment – Circular economy index

Figure 2.21 shows a general trend for decreasing PED demand with higher priority levels in the FLW hierarchy. Negative values of $EROI_{ce}$ indicate that the energy recovered from the management of FLW is larger than the energy requirements for its management. As shown, landfilling with biogas recovery (Scenario 1: L) do not recover enough energy to compensate the energy expenses of the treatment. AD&C (Scenario 3: AD&C) seem to be the best option for the food categories assessed. An exception is suggested for vegetables FLW, for which a larger PED is observed for Scenario 2, involving higher energy recovery from the incineration treatment. This may be due to the fact that the fermentation period is longer than the rest of the categories and therefore requires a higher energy consumption.

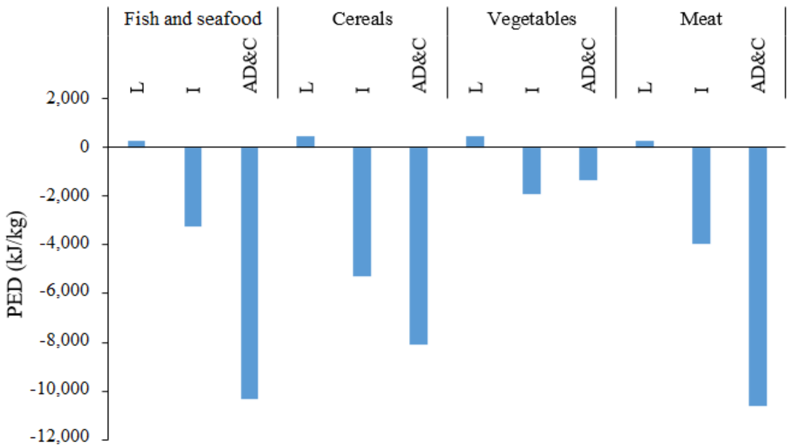

Figure 2.21 Primary energy demand values for the considered scenarios expressed in kilojoules per kilogram.

Afterwards, $EROI_{ce}$ scores have been assessed. Results from Figure 2.22 suggest that AD&C is the best FLW management strategy. On the other hand, it is highlighted that cereals are the category with the highest potential for energy recovery, with values between 20 and 28 times higher than the rest of the categories, regardless of the scenario. This is undoubtedly influenced by the fact that it has the highest FEL value, representing 44% of the total. Finally, it is observed that vegetables appear again as the less energy efficient category, owing to the low energy recovered from its FLW management, which could be due to a low carbon content (the numerical results can be consulted in table A1.13 of the Annexes).

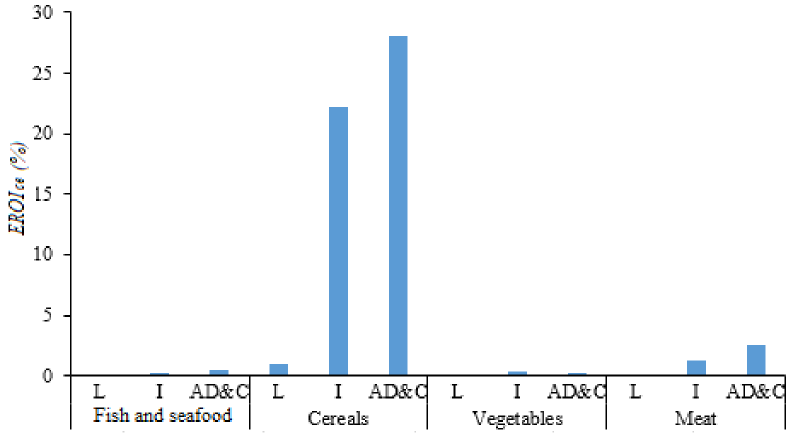

Figure 2.22 Energy return on investment – Circular economy index for the considered scenarios.

2.3.4 Discussion

The results of the energy flow analysis determined a total EEL value of 17% in relation to the total PED along the entire supply chain, showing the consumption stage as the most inefficient one. This is in accordance with Vittuari et al. (2016), who assumed that embodied energy builds up along the chain, so the latter the FLW occurs, the greater the energy loss. The EEL results indicate that in the final part of the FSC, which means the sum of the distribution stage plus the consumption stage, the highest amount of EEL is concentrated. The FEL results point out that the stage of consumption is the one with the highest values. Moreover, if the FEL values for agricultural production and processing and packaging are added, it is suggested that the first part of the FSC accumulate the highest FEL. These results highlight the option of decentralize the energy recovery strategies, which could improve the efficiency in the FLW management systems, by installing energy recovery plants at the beginning and at the end of the FSC.

Regarding the nutritional assessment in terms of EEL, vegetarian and pescetarian diets appear to be the most efficient ones. In this sense, several studies have supported similar thesis taking into account different approaches such as the GHG emissions (Berners-Lee et al., 2012) and the economic value of FLW (presented in Section 2.2).

From the FEL results, the high loss value generated by the cereals category (44%) is remarkable. After assessing the $EROI_{ce}$ scores, results also suggest that cereals is the category with higher potential for energy recovery. In addition, in three of the four categories analyzed, results show a general trend for decreasing PED with higher priority levels in the FLW hierarchy (Eriksson et al., 2015), standing out the AD&C as the most appropriate for FLW management. This reinforces the thesis that FLW is an attractive substrate for AD&C because of its low total solids and high content of soluble organics, as stated by David et al. (2018). In this sense, the development of decentralized energy recovery strategies through AD&C could be proposed, as opposed to centralized strategies, which are large scale for the treatment of FLW (Wang, 2014).

Following the previous context, new strategies for the different fractions of FLW and its compositions could be introduced in order to meet the transition towards a more circular economy (Arushanyan et al., 2017). In this case, the cereal fraction stands out in terms of the amount of FEL and the amount of food that can be reintroduced into the FSC. In this sense, until now, AD&C has usually been focused on the recovery of biogas in form of methane mainly. In view of the high energy recovery potential of cereals and their high level of hydrocarbons in their chemical composition, it is suggested their separately management, based on the works of Kibbler et al. (2018) and Bernstad and La Cour (2012). Due to its composition, it is considered that they have a high potential for the recovery of bioenergy in form of hydrogen. Therefore, this proposal of decentralization would include the development of two types of AD&C digesters: one for the cereal fraction with hydrogen recovery, and another for the rest of FLW, with methane recovery, as can be seen in Figure 2.23.

Decentralized AD&C plants of biogas production from organic waste and FLW, could have clear advantages in concrete contexts like rural regions, and other local economies, which are far away from power sources (De Souza et al., 2018). This has already been tested in many rural contexts around the world, existing good and diverse examples, as the works developed by Raha et al. (2014) in India, and Kelebe and Olorunnisola (2016) in Ethiopia. Another argument in favor of this decentralization option is the fact that valorization in form of biogas is, generally, more applicable when there is homogeneity of the waste (Girotto et al., 2016), and homogeneous FLW streams are most likely generated before being mixed with the rest of the FLW (De Laurentiis et al., 2018). In this sense, there are several technological challenges that require future research in order to deploy this technology for small and medium applications.

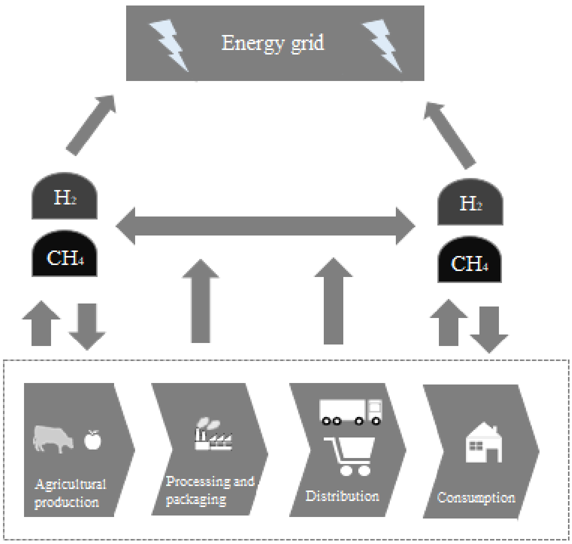

Figure 2.23 Outline of the proposed energy recovery strategies.

One of the main barriers for those strategies is the wide variation of feedstock and environmental conditions (e.g., temperature) over space and time, which are more difficult to control through small-decentralized digesters. Additionally, it is important to know that from an energetic point of view, small scale AD&C hardly can perform a strong separation between biodegradable and non-biodegradable fraction. If a stronger pre-treatment is demanded, local AD can become impracticable from both an energy and economic point of view (Wang, 2014). On the other hand, the decentralized management option could also be applied to the consumption stage, as it is a very simple system (Lundie and Peters, 2005). It could be an especially interesting alternative in buildings where a large number of people are living, receiving a high and constant source of power to produce energy, for self-consumption in the first instance, and to sell to the electricity grid if consumption is less than production. As a practical example, a recent study in this field, carried out by Walker et al. (2017), analyzed systems of micro-scale AD in London, showing that this technology could provide a useful means of processing FLW in urban areas.

The proposed change of strategies poses the debate of the 'sustainable degrowth' sustained by Infante-Amate and González de Molina (2013) and Latouche (2006), which emerged as a strategy that aims to generate new social values and new policies capable of satisfying human requirements whilst reducing the consumption of resources. In Chapter 5, the degrowth movement and its relation with the food production and the FLW management systems will be assessed. It is also intended to support the EU action plan for the transition to a more circular economy (EC, 2015), and the Bioeconomy Strategy (EC, 2012), contributing to meet the objectives of bioenergy and the sustainable use of renewable sources, through the replacement of fossil fuel by renewable raw materials and the replacement of chemical processes by biological ones.

2.3.5 Conclusions

The energy flow analysis developed in this work suggest that to produce 1 kJ of nutritional energy, 8.7 kJ of primary energy is required, being the distribution and agricultural production stages the ones that require the most primary energy, respectively. From the 11 categories studied, the ones with the lowest EROI are fish and seafood, vegetables, meat and pulses. In terms of EEL, consumption is the stage with the highest values, representing more than 66% of the total in the whole FSC. The total sum of the obtained EEL results was 17% of the total PED. Meat, cereals, vegetables and fish and seafood have the highest values, which together accounts for almost 84% of the total Spanish EEL. If the four categories of products of animal origin are added, it is highlighted the fact that around 50% of the total EEL is due to these products. In terms of FEL, cereals, vegetable oils, meat and sweets, represent the highest values. The stage of consumption is clearly the one with the highest FEL value, although the beginning of the FSC would represent a higher FEL if agricultural production and processing and packaging values are added. The distribution stage, despite being the one that requires the most PED, is at the same time the one that clearly generates less FEL (7.4%).

The study suggests that the efficiency of energy of the agri-food supply depends heavily on the food category under study. Meat and fish and seafood have a very high PED to produce less food. Also, according to the $EROI_{ce}$ it is highlighted that cereals is the category with the highest potential for energy recovery from FLW, with values between 20 and 28 times higher than the rest of the categories. Related to the results, it is suggested that energy recovered from FLW can contribute considerably to the national energy grid, as well as to energy self-consumption throughout the FSC. This could contribute to reduce the environmental costs, the demand of other types of non-clean energies such as coal- and nuclear- energy, and to produce new food from the recovered energy. Although up to now the collection of FLW is usually done in a centralized way, the use of AD&C for decentralized biogas production is, according to this work, one of the most potential technologies of bioenergy generation. It offers a good option of local FLW management, which reduces the environmental impact due to transport, and encourages self-consumption, as well as benefiting the economy of local actors. Moreover, the recovery of energy in form of biogas can occur through the generation of different products. In this sense, an approach of possible treatment strategies for residues of cereals with hydrogen recovery and mixed FLW with methane recovery, has been made. It is considered that the diversification and decentralization in FLW energy recovery strategies could facilitate the transition to a more circular economy. The efficiency of the suggested strategies could be further improved by intensifying research and optimization studies. Thus, basic research is critical in order to advance the development of those technologies. Results from the study allows to facilitate the decision-making process for the proper FLW management, developing a general awareness on the need of energy-smart strategies or policies, which are decentralized and adapted to each stage of the FSC and the different fractions of food. This claim is in contrast to the waste hierarchy of the EU, which is considered as a too generic proposal. Specifically, this work aims to highlight the need to address a decentralized and diverse FLW management, in order to manage more efficiently the different fractions, and at each of the different stages of the FSC. Future works should: (i) simulate different scenarios of decentralized management, (ii) put into practice the cases of pilot studies already carried out, and (iii) optimize systems on a larger scale through the intervention of small-scale systems throughout the FSC for which it is fundamental to establish regional strategies that support the already established global ones. Thus, the general objective of this research field is to follow strategies that act locally to achieve global development.

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CHAPTER 3

Regionalized assessment: environmental impacts and water footprint

3.1. Framework

The third chapter of this Thesis moves from a national analysis to a regional approach, by presenting a regionalized assessment of different FLW management scenarios at the 17 regions of Spain. The study develops different scenarios over time using the simulations of an energy system model for the assessment of the potentially evolution of the situation from 2015 until 2040. Through it, it is aim to reach the **Objective 5**, of facilitating the decision-making process at regional level, suggesting scenarios that will lead to the environmental sustainability, as well as to reduce the environmental cost of food production systems in Spain. Chapter 3 is divided in two sections, based in a published paper and a paper in press:

1. Hoehn D, Laso J, Cristóbal J, Butnar I, Borrion A, Bala A, Fullana-i-Palmer P, Vázquez-Rowe I, Aldaco R, Margallo M **(2020)** Regionalized Strategies for Food Loss Management in Spain under a Life Cycle Thinking Approach. *Sustainability* 9(12), 1765.
2. Hoehn D, Margallo M, Laso J, Ruiz-Salmón I, Vázquez-Rowe I, Aldaco R, Quinteiro P **(2021)** Water footprint assessment for best-regionalized strategies for food loss and waste management in Spain (*in press*).

3.2. Regionalized strategies for food loss and waste management in Spain under a life cycle thinking approach

3.2.1 Introduction

Renewable energy production policies in Spain are determined by the international context and EU recommendations, which are looking for a more sustainable and low-carbon economy to achieve the Paris Agreement targets. Among them, the goal of limiting global warming to well below 2°C above pre-industrial levels and pursuing efforts to limit it to 1.5°C stands out (UN, 2015). Based on the horizon of the EU being carbon neutral by 2050, the EU has established the specific objectives of reducing GHG emissions by 40% in 2030 as compared to 1990, which includes an aim of having a share of 32% of renewable energy production (IDAE, 2020). Consequently, in 2019, the Spanish government included the EU targets (EC, 2020b) in the draft of the Integrated National Energy and Climate Plan 2021-2030, which aims to integrate the environmental, economic, and social benefits of energy transition in the Spanish economy. To achieve these objectives, the coordination and active involvement of the 17 Spanish regions is essential, considering that Spain has a heavily decentralized legislative system, which implies that decision-making is partially regionalized.

In this framework, the energy produced from non-fossil organic material of biological origin, so-called bioenergy, is being promoted as a substitute for non-renewable energy to reduce GHG emissions and dependency on energy imports (Haberl et al., 2010). Nowadays, bioenergy accounts for ca. 18.5% of renewable energy consumption in the EU (EC, 2017), but less than 1.1 % in Spain (Red Eléctrica de España, 2019). However, from all the sources of bioenergy, use of solid biomass, biogas, liquid biofuels, and renewable municipal waste, what kind of resource should be used for power generation is an open question owing to environmental, ethical-social, and economic aspects. FLW, has been widely suggested as an alternative to biofuel production (Kiran et al., 2014) due to its organic and nutrient-rich composition, representing a potential global warming mitigation path (Gintouli et al., 2016). In addition, using FLW as a bioenergy source could significantly contribute to a close carbon cycle (Secondi et al., 2015) by reintroducing energy in the FSC (Maisarah et al., 2018). However, the potential contribution of FLW to renewable energy generation is often disregarded when discussing on FLW management.

In Spain, an important fraction of FLW is still landfilled. The remaining waste is being managed in the 10 existing incineration (thermal treatment) plants (in form of refuse-derived fuel), or in mechanical-biological treatment stations, based on AC or AD systems, whereas pre-treated FLW (i.e., the remaining matter after the treatment) is sent back to landfill or incineration plants. In recent years, the source-separation of the specific AD plants has been reduced to a few pilot projects.

In this framework, while in the previous chapter an assessment of the FLW generation was developed in different aspects at a national level, in this chapter, the analysis delves into a regional assessment regarding the 17 Spanish regions, in order to analyze different environmental impacts. All it, by simulating different scenarios, searching for the most optimal strategy within the same region in a framework of compliance and non-compliance with the Paris Agreement targets. All it using prospective LCA. Therefore, the evaluation of the environmental performance over time between 2015 and 2040 of a scenario showing the current FLW management at each region, and five different management scenarios implemented in a framework of i) compliance (2DS) and ii) non-compliance with the Paris Agreement targets (BAU), was performed. As represented in Figure 3.1, the work developed in this section aims to highlight the need of developing regionalized FLW management policies to steer Spanish policymaking to move from a national to a regional approach when developing future roadmaps, as well as integrating FLW management and renewable energy policies.

3.2.2 Materials and Methods

Goal definition

The main goal of Section 3.2, by conducting an LCA following the international standards ISO 14040 (2006) and ISO 14044 (2006), is to determine the most optimal scenario of FLW management regarding each of the 17 Spanish regions. As previously mentioned, LCA is a standardized methodology for analyzing the potential environmental impacts of a product, process, or service throughout its life cycle (Pirlo et al., 2016), which has been widely applied to improve the design or to optimize a wide range of production processes (García-Herrero et al., 2017). The current FLW management in each region is compared to five alternative scenarios regarding the type of FLW treatment, which are described below. The environmental performance of these scenarios was evaluated for the period 2015-2040 considering the compliance (2DS) and non-compliance (BAU) with the Paris Agreement targets. The simulations over time are based on the energy mix projections developed by the TIAM-UCL. It considers 16 regions covering all the world (Anandarajah et al., 2011). For this study, data for the Western European Region, that includes Spain, were used.

Function and functional unit

The main function of the system is the management of FLW under different scenarios simulated. In order to measure this function, a suitable functional unit has to be defined, to which all the inputs and outputs are referred. In this case, the treatment of one metric ton of FLW in each Spanish region in the respective year of analysis was assumed as the functional unit.

System boundaries

This LCA has a cradle to grave approach (Figure 3.1), including within the system boundaries the FL generation in the first stages of the FSC - agricultural production, processing and packaging -, and FW in the distribution, and consumption stages. FLW was divided into 11 categories of food, following the division suggested by FAOSTAT (FAO, 2014), which considers cereals, sweets, vegetable oils, vegetables, fruits, pulses, roots, dairy products, eggs, fish and seafood, and meat. Collection and transportation of FLW to the different management alternatives were not considered in the system boundaries since it was assumed similar environmental loads for all the FLW management options, due to its low influence. The mass balances from Section 2.2 (Chapter 2) have been used in order to consider FLW of different food categories. Regarding FLW management, AC, AD, incineration, and landfill were evaluated. To determine the FLW generated in the four stages of the FSC and the amount of FLW treated at each management option, the data published in different Spanish governmental sources, have been used. The autonomous cities of Ceuta and Melilla were left out of the scope of the study considering their low demographic weight (< 0.4%). Both edible and non-edible FLW fractions collected were also considered.

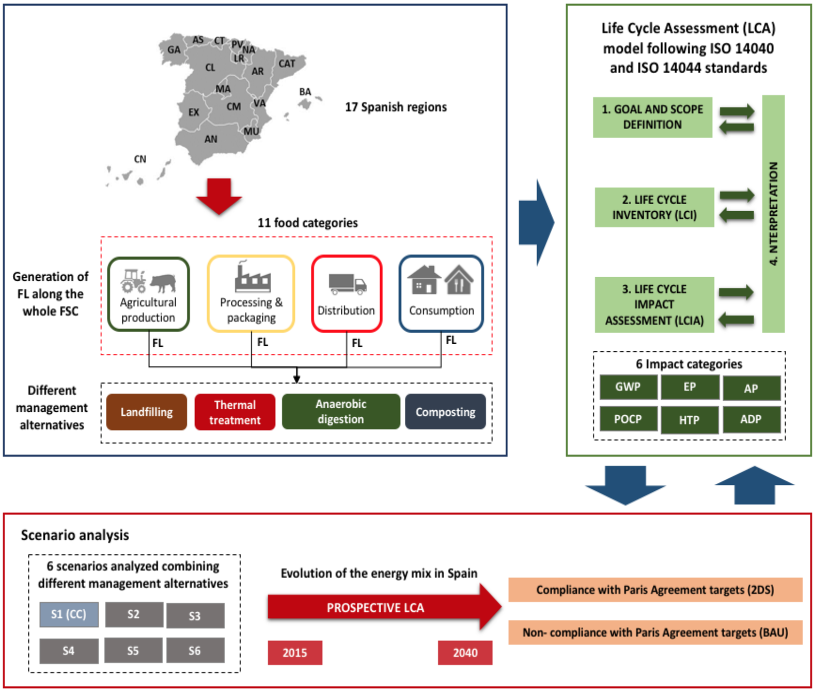

Figure 3.1 Conceptual diagram of the life cycle assessment methodology developed, based on Aldaco et al. (2019). GWP: Global Warming Potential; EP: Eutrophication Potential; AP; Acidification Potential; POCP: Photochemical Ozone Creation Potential; HTP: Human Toxicity Potential; ADP: Abiotic Depletion Potential; 2DS: compliance with the Paris Agreement targets; BAU: non-compliance with the Paris Agreement targets; FSC: food supply chain; FLW: food loss and waste.

Scenarios under study

In order to determine the most optimal FLW management strategies for the 17 regions, six different scenarios, including the baseline scenario (S1), are analyzed within this study by implementing them in all regions and all the analyzed years (as summarized in Table 3.1).

- **Scenario 1 (S1)**. It represents the baseline scenario taking into account the current FLW management in each region (shown in Table 3.2), according to data published by the Spanish Waste Management Framework Plan (PEMAR, 2015) and the CONAMA Foundation (2014). The results of S1 are calculated using the best-founded data for 2015, combined with certain assumptions.
- **Scenario 2 (S2)**. It replicates the current situation in Germany regarding FLW management (DBFZ, 2017), where AC represents the highly part of the treatment, but AD systems are increasingly being promoted. Therefore, it is considered that 75% of FLW is going to AC, 20% to AD and the rest is divided between landfill (2.5%) and incineration (2.5%).
- **Scenario 3 (S3)**. This scenario prioritizes the use of AD systems, assuming that 75% goes to AD, 20% to AC, and the rest is divided between landfill (2.5%) and incineration (2.5%).
- **Scenario 4 (S4)**. This scenario is based on current Danish conditions, where over 90% of the share of bio-waste is incinerated (Bang-Jensen et al., 2016). Thus, 90% of FLW goes to incineration, while the rest “10%” goes to landfill, AD and respectively AC in equal proportions.
- **Scenario 5 (S5)**. This scenario is based on the increasingly promoted claim that FLW is a valuable resource that should never end up in landfilling sites (Vision 2020, 2013). It is assumed that landfilling is not a FLW management alternative, so 33.3% goes to each of the remaining management options.
- **Scenario 6 (S6)**. Landfilling and incineration are not considered in this scenario, so 50% of FLW is treated in AC, and 50% in AD. The argument for avoid including incineration plants in S6 refers to the fact that, similarly to what has recently occurred to coal plants in many nations including Spain, incineration plants will potentially have problems to provide energy to the system by the year 2030. More specifically, they will have serious difficulties to maintain competitiveness against other technologies in an environment highly conditioned by the European response to climate change, in which the cost of CO_2 will tend to be increasingly higher (IDAE, 2019).

Table 3.1 Simulated scenarios of FLW management in Spanish regions. Scenarios S2 to S6 comply with the Directive 1999/31/EC on the landfill of waste (EC, 1999).

Scenarios	Landfill	Incineration	AD	AC
S1	Dependent on each region (see Table 2)			
S2	2.5%	2.5%	20%	75%
S3	2.5%	2.5%	75%	20%
S4	3.3%	90%	3.3%	3.3%
S5	-	33.3%	33.3%	33.3%
S6	-	-	50%	50%

The scenarios simulated were studied taking into account the evolution of the electricity mix in Spain from 2015 to 2040 in the 2DS and BAU frameworks (as described below).

For the modelling of FLW generation in each region, the FLW composition was considered (see Figure 3.2). Therefore, a literature review was done in order to determine the management possibilities of each FLW fraction regarding regulatory and technical issues (as shown in Table 3.3). The highest priority are prevention and re-use, understanding by re-use the use of the materials without further processing, for instance, food donation to charities. AC has regulatory restrictions for animal products and vegetable oils (Composta en Red, 2012). Therefore, AC was not included for the management of vegetable oils, meat, fish and seafood, dairy products and eggs. Those residues were assumed to go to the main FLW management option in each scenario and, following the waste hierarchy, prioritizing AD and incineration over landfill. Consequently, those fractions were assumed to go to landfilling in S1, to AD in S2, S3 and S6, to incineration in S4, and 50% to incineration and 50% to AD in S5. Moreover, as incineration generates 15-25% of ashes (Ammann, 2011), including bottom and fly ashes, an average value of 20% was assumed to go to landfilling in regions with incineration plants.

Table 3.2 Amount of FLW by treatment and region in 2015. Data represented in percentages calculated from mass balances in metric tons reported for each region. Regions: AN: Andalusia; AR: Aragon; AS: Principality of Asturias; BA: Balearic Islands; CN: Canary Islands; CT: Cantabria; CM: Castile-La Mancha; CL: Castile and Leon; CAT: Catalonia; EX: Extremadura; GA: Galicia; LR: La Rioja; MA: Community of Madrid; MU: Region of Murcia; NA: Chartered Community of Navarra; PV: Basque Country; VA: Valencian Community; SP: Spain.

Region	Landfill	Incineration	AD	AC
AN	93.8%	-	2.3%	3.9%
AR	62.0%	-	3.0%	-
AS	92.1%	-	-	7.9%
BA	18.9%	72.7%	5.1%	3.3%
CN	95.7%	-	4.3%	-
CT	35.1%	64.9%	-	-
CM	100%	-	-	-
CL	56.4%	-	43.6%	-
CAT	49.4%	18.4%	15.7%	16.5%
EX	100%	-	-	-
GA	33.6%	50.6%	14.9%	0.9%
LR	35.1%	-	64.9%	-
MA	63.4%	10.6%	25.5%	0.5%
MU	100%	-	-	-
NA	61.4%	-	26.6%	12.1%
PV	65.9%	25.3%	6.7%	2.1%
VA	75.9%	-	21.6%	2.5%
SP	**68.8%**	**11.9%**	**14.9%**	**4.5%**

Life cycle inventory

A set of assumptions and calculations were carried out to develop the life cycle inventory of FLW generation and management in the 17 regions regarding the four stages of the FSC, the 11 FLW categories, and the four management options considered.

Table 3.3 Different possibilities of FLW management combining the waste hierarchy framework with regulatory issues limiting the use of animal products (Composta en Red, 2012, EC, 2011) and technical issues allowing the industrial use of recycled vegetable oils (BOE, 2011).

Food loss and waste management	Cereals	Roots and tubers	Sweets	Vegetable oils	Vegetables	Fruits	Pulses	Meat	Fish and seafood	Dairy products	Eggs
Prevention	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Re-use	✓	✓	✓	✓	✓	✓	✓	✗[a]	✗[a]	✗[a]	✗[a]
Animal feed	✓	✓	✓	✓	✓	✓	✓	✗[a]	✗[a]	✗[a]	✗[a]
Industrial use	✗	✗	✗	✓[b]	✗	✗	✗	✗	✗	✗	✗
AC[c]	✓	✓	✓	✓	✓	✓	✓	✗[a]	✗[a]	✗[a]	✗[a]
AD[c]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Incineration[c]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Landfill[c]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

[a] regulatory issue, [b] technical issues, [c] FLW management considered in this work.

To calculate the data for the stages of agricultural production, and processing and packaging, data reported by the Spanish Ministry of Agriculture, Fishery and Food (ESYRCE, 2019, Informe Anual de Industria, 2017) were used to determine the percentage of livestock, agricultural or fishery production, as well as the number of existing industries, in each region, from the total values reported. Regarding the distribution and household stages, the calculations were based on the existing population in 2015 (INE, 2015), adding as a part of the population the number of tourists in each region in that year (INE, 2016). Finally, it was assumed that FLW accounts for 49% from total reported waste (CONAMA, 2014). A detailed description is reported in Figure 3.2 and detailed in Table A2.1 of the Annexes.

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

- AC was modelled using the professional database of the GaBi software (Sphera, 2019), which considers closed halls or so-called composting boxes or rotting tunnels. The input waste is assumed as an average mixture of biodegradable waste consisting of biodegradable garden and park waste, as well as a 35% content of food and kitchen waste. For the selective collection fraction, the composting system includes the energy requirements of a mechanical separation unit (Cimpan and Wenzel, 2013).
- AD was modelled using the Ecoinvent database (2016), including storage of the substrates, anaerobic fermentation, as well as the storage of digestate after fermentation. One cubic meter of biogas is assumed to produce 2.07 kWh of electricity (Junta de Andalucía, 2011).
- Incineration was based on the professional database of the GaBi software (Sphera, 2019) for the biodegradable waste fraction of municipal solid waste (MSW). To model a single fraction, energy production and credits 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 plants in Spain (Margallo et al., 2014). The incineration of one metric ton of waste produces 495 MJ of energy, 1,277 MJ of

steam, 220 kg of bottom ash, and 42 kg of boiler ash, filter cake and slurries.

- Landfill with biogas recovery, includes biogas and leachate treatment and deposition. Sealing materials (e.g. clay or mineral coating) and diesel for the compactor were also included. The modelling was based on the landfill process for municipal household waste from the professional database of GaBi software (Sphera, 2019). According to the model, 17% of the biogas naturally released is 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 FLW was assumed (Sphera, 2019).

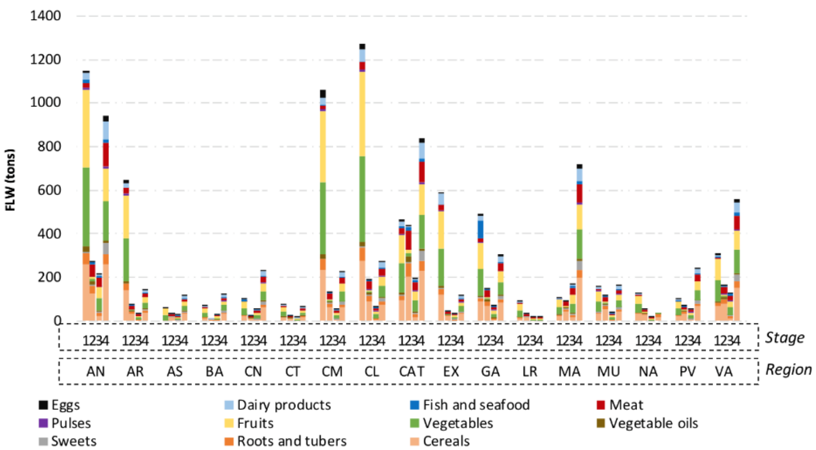

Figure 3.2 FLW generation at each region (in tons) in 2015, divided in the 11 food categories and four stages considered. Stages: 1: agricultural production; 2: processing and packaging; 3: distribution; and 4: consumption. Regions: AN: Andalusia; AR: Aragon; AS: Principality of Asturias; BA: Balearic Islands; CN: Canary Islands; CT: Cantabria; CM: Castile-La Mancha; CL: Castile and Leon; CAT: Catalonia; EX: Extremadura; GA: Galicia; LR: La Rioja; MA: Community of Madrid; MU: Region of Murcia; NA: Chartered Community of Navarra; PV: Basque Country; VA: Valencian Community.

The avoided burden for electricity from AD, incineration and landfill, are based on the electricity mix simulations according to the TIAM-UCL model, which are shown in Figure 3.3. The evolution in a BAU framework suggests continuous increase in the energy produced from coal, reaching by 2040 around 60% of the total energy generation, followed by hydropower (20%), and natural gas, with less than 10% (as seen in Figure 3.3a). Biomass and biomass with carbon capture sequestration will begin to decrease starting in 2025 until almost disappearing by 2040. Regarding the evolution in a 2DS framework (Figure 3.3b), surprisingly, nuclear power seems to have an enormous increase, reaching 55% of the total electricity mix in 2040, followed by hydropower (20%) and onshore wind (10%). This highlights that certain decarbonization policies in the electricity sector may foster the rise of a controversial energy source (i.e., nuclear), which opens the debate on whether the final outcome justifies any strategy to meet the Paris Agreement targets. This fact, suggested another policy advice, which would be complementary and necessary together with climate policies, existing previous experiences such as the ban of nuclear power developed in 1978 in Austria (BGBI, 1978). Finally, both options suggested a reduction of the energy generated by biomass in 2025, which nearly disappears by 2040.

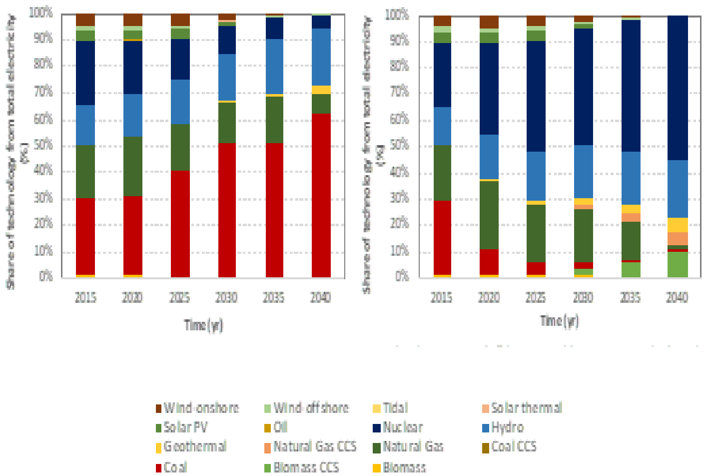

Figure 3.3 Energy mix simulations according to the TIAM-UCL model for Western European region. (**a**) Simulated BAU and (**b**) 2DS energy mix frameworks from 2015 until 2040. PV: photovoltaic; CCS: carbon capture sequestration. Biomass includes waste-to-energy technology such as incineration (thermal treatment).

System expansion

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, steam and compost are additional functions. Therefore, the environmental burdens must be allocated among the different functions. To handle this problem, ISO 14040 (2006) establishes a specific allocation procedure in which system expansion should be prioritized. The energy produced in waste decomposition (i.e., landfill and AD) and combustion (i.e., incineration) was assumed to substitute the equivalent amount of electricity from the grid. 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. 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 (Arcadis, 2010). The fertilizer production as total N was obtained from the professional database of the GaBi software (Sphera, 2019).

Life cycle impact assessment

In order to quantify the potential environmental impacts of the scenarios modelled, six environmental impact categories (shown in Table 3.4) were selected from the CML v3.06 methodology (Guinée et al., 2002). This choice was made considering that the assessment method has enough scientific endorsement and is widely used in the LCA literature (Guinée, 2015).

Table 3.4 Environmental impact categories assessed using the CML method.

Impact category group	Name	Acronym	Unit
Acidification	Acidification Potential	AP	kg SO_2 equivalent
Climate change	Global Warming Potential (excl. biogenic carbon) over a 100-year time	GWP	kg CO_2 equivalent
Depletion of abiotic resources	Abiotic Depletion elements	ADP	kg Sb equivalent
Eutrophication	Eutrophication Potential	EP	kg Phosphate equivalent
Human Toxicity	Human Toxicity Potential	HTP	kg DCB Equivalent
Photochemical oxidation	Photochemical Ozone Creation Potential	POCP	kg ethene Equivalent

The selection of impact categories was done considering the most relevant impacts linked to organic waste and its treatment. In this sense, climate change, due to anaerobic organic decomposition, was highlighted as an important indicator to be considered. The presence of different waste treatment technologies, namely incineration, pushed towards the inclusion of human toxicity and air quality categories, such as photochemical oxidation. Acidification and eutrophication were selected due to the presence of acidic gases and high amounts of nutrients in FLW, respectively. Finally, abiotic depletion was modelled considering the displacement of fossil fuels and resources in the systems in which electricity and fertilizers are generated from FLW. It is acknowledged that other assessment methods could have been chosen to conduct certain impact categories, but the use of one single method constructed with the same methodological basis was prioritized.

Main limitations and assumptions of the study

The main limitation of the present study is the uncertainty in the data used, being the main sources of uncertainty the amounts of FLW generated and the type of management for the different FLW categories in the reference year, as well as the trends until and during the modelled time. Moreover, it is difficult to link FLW generation and management, as the whole process takes time and in the meantime a fraction of the mass might be lost (e.g., due to drying). Differences can occur also due to import and export of waste, as well as unaccounted fractions. Moreover, although information is available regarding the different treatment and disposal methods, existing statistics generally refer to the generation of biodegradable municipal waste, not to the generation of bio-waste or FLW (Arcadis, 2010). Biodegradable municipal waste also includes paper, cardboard and biodegradable textiles. Additionally, in the more advanced stages of the FSC, FLW is usually mixed with general waste, which complicates the determination of the percentage that corresponds to FLW exclusively. In this framework, the modelling of the incineration process of FLW has a considerable degree of uncertainty, as the provided processes are not specifically adapted to individual waste streams, and biodegradable waste was used instead of FLW, which means a partially different heating value. The combustion of FLW produces dioxins and furans depending on ranges of temperatures (from 250 to 400°C). Nevertheless, one limitation of toxicity categories in LCA is the fact, that most of the methods do not include a characterization factor for these pollutants, providing an uncertainty source in the results. This limitation was found in CML method, but it is common in other impact methods, such as ReCiPe, both of them widely applied for LCA practitioners. Moreover, is important to highlight that the assumed source-separation of the FLW mentioned fractions (described in the Life cycle inventory Section) is a mainly theoretical process, with the exception of some industrial waste streams. Additionally, how difference of FLW composition will affect its management, have been only considered regarding the restrictions in the use of animal products in AC. Other factors such as biogas generation and moisture content have not been included in the calculations. How those aspects would influence the management process would be another relevant element to include within the system boundaries, which was not analyzed in this work. The amount of FLW also depends on factors such as the time of the year and the region. Thereby, this study deals with a field where there are important gaps in the clarity of the reported data, both in terms of the generated quantities of FLW, and in terms of the relative importance of different recovery or disposal options. Regarding the AC process, it considers the use of the digestate in soils, avoiding thereby the use of fertilizers. Nevertheless, the potentially methane emissions due to the direct use in soil have not been assessed. In addition, it is important to highlight that the positive impact on environment provided by compost is underestimated by the current LCA methodology when it is compared to digestate. This is due to the fact that when digestate after AD processing is employed, most of the carbon content is already used as methane and the quality of digestate cannot be compared to compost.

A debatable assumption made in this study concerns the selection of the LCA approach to solve the multi-functionality issue mentioned before in the Life cycle inventory Section. This study has used an attributional approach in which the electricity produced within the system boundaries is sent to the grid, and thus the system is credited with the impacts of producing that amount of electricity using average data from the electricity mix. On the other hand, the selection of a consequential approach would have identified the marginal technology from the mix displaced by the energy produced within the system boundaries and thus, the system would be credited with the impacts of producing that amount of electricity using that displaced technology. According to the literature, the selection of one approach or the other can have an important effect on results and conclusions drawn from LCA for solid waste management systems Bernstad et al. (2017). Moreover, technological developments related to the FLW management methods, such as improving the electricity production efficiency or cleaning exhaust gas technology, were not considered in this analysis.

Additionally, the evolution of the FLW generation until 2040 was firstly considered, using a logarithmic regression based on the projection of the World Bank Group (2018) regarding the Spanish population growth. Thereby, a progressive and cumulative increase was assumed, reaching 6.7% in 2040 compared to 2015. Since, given the construction of the scenario simulation model, this increase did not generate any change; this process was omitted from the methodology. For the same reason, the SDG12.3 target, aiming to reduce food waste until 2030 by 50%, which was an important reason for recent EU legislation which set an obligation for EU member states to measure and report food waste along the FSC from 2020 onwards (EC, 2019), was not included in the modelling process. Both facts may be another source of uncertainty and limitation in the results of the work.

Finally, it is important to remark that each simulation will always represent a simplification of reality.

3.2.3 Results and discussion

Within this section, results from two different analysis are presented and discussed. The first part is focused on the current Spanish regional FLW management configuration (scenario 1). The environmental performance of the 17 regions is analyzed considering future periods and maintaining the Scenario 1 configuration under different political decisions (i.e., fulfill the Paris Agreement targets or not). The second part is focused on the possibility of changing the FLW management configuration (scenarios 2 to 6) also under different political decisions (i.e., fulfill the Paris Agreement targets or not) analyzing the environmental performance and a regionalized analysis of the GWP impact category, as an example, for those configurations. Finally, the third part presents a comparison of the results with previous published studies within this topic.

Environmental impacts of the current Spanish regional food loss and waste management: Scenario 1

Due to the heterogeneity of the management strategies implemented in the 17 Spanish regions (shown in Table 3.2), that would be maintained until 2040 for this scenario, the environmental performance results differ greatly between regions. In order to see if the future environmental performance is better or worse, impact results by category for a future time period are represented as the ratio between the impact for that period and the impact in 2015. Herein, results are discussed according to two different variables: the influence of the FLW management technologies and the influence of the Paris Agreement framework (reflected in the evolution of the electricity mix). Attending the trends and similarity in results, regions are clustered. Results for one representing region are depicted in Figure 3.4.

In order to see the influence of the different FLW management technologies, one cluster of regions can be done for CT, BA, GA, and PV, where incineration plays an important role (more than 25%). Thus, results show that the use of incineration is related to a significant decrease in ADP (up to 15%), as it presents the highest level of energy generation and, therefore, the greatest savings in terms of resources consumption are achieved. Figure 3.4a and 3.4b shows the results for CT under BAU and respectively 2DS, whereas BA, GA and PV with a similar trend, are included in Figure A2.1 of the Annexes.

A second cluster of regions can be done for AN, AS, CM, CN, EX, and MU, where FLW management is carried out almost entirely through landfilling with energy recovery (between 92% and 100%). Figure 3.4c and 3.4d show the environmental burdens for EX under BAU and respectively 2DS, the rest of regions are represented in Figure A2.1 of the Annexes. Results show that the use of landfilling is related to a significant increase in ADP (up to 35%) under both BAU and 2DS futures.

A third group of regions are those that combine the use of landfilling and AD (i.e., AR, CL, LR, MA, and VA), with AD percentages ranging from 22% to 67%. All these obtained similar results with an increase in the consumption of ADP over time (up to 58% for VA, as shown in Figure 3.4e). The higher the percentage of AD, the higher the ADP values (Figure A2.1 of the Annexes).

A fourth group of regions is composed by CAT and NA, in which AC reaches values of 19% and 12%, respectively (Figure 3.4g for NA). This figure suggests the biggest increase in ADP, higher than that observed in the previous clusters, although the trends are similar to clusters 2 and 3. This is related to the fact that it is the only management option that does not generate energy, and therefore the consumption of abiotic resources through the energy mixes increases much more than in the previous clusters. According to the developed model, the fact of generating organic fertilizer through AC, which constitutes an avoided burden with respect to the environmental impacts of the fertilizer that would normally be used, has a much lower importance, in terms of ADP, than the fact of not generating energy that would displace other non-renewable sources in the energy mix. Concerning the impact categories of GWP, EP, POCP and HT, there is always a slight increase over time across all clusters. This increase is more pronounced in FLW management configurations that present high rates of incineration.

Analyzing the influence of the Paris Agreement framework on the results, the relation is clear for some impact categories and technologies. The energy mix has a great influence on the AP impact category. Results show big decrease in AP for the 2DS when landfill is the main technology in the FLW configuration (clusters 2 and 3), since the electricity mix, with higher weight of renewable sources, has a lower environmental burden in AP. However, this is not visible in the configuration with a high share of incineration (cluster 1). In this case, figure 3.4a shows a reduction in AP in the BAU scenario (up to 21% in the case of GA), in which the energy from FLW incineration has a lower load of acid gases than the one that would be obtained from the energy mix strongly marked by the presence of fossil fuels such as coal and natural gas. Under the 2DS, the reduction in acid gases related to the electricity mix is overcompensated by the acid gases from incinerating FLW, resulting into increased AP. Regarding ADP, values are always positive (increase from 2015) and higher for BAU comparing to 2DS, except for the configurations in which incineration plays a key role. In the latter case, figures 3.4a and 3.4b suggest a reduction in the consumption of abiotic resources, which is less pronounced in the 2DS framework (up to 9%), since the energy obtained from incineration is replaced by cleaner energy that uses more renewable sources.

This entails lower environmental savings or avoided burdens and, thus, a higher impact is obtained. This is the case of CT, BA and GA and PV, which reduced up to 15% the ADP impact in the BAU framework.

Concerning the impact categories of GWP, EP, POCP and HT, as mentioned before, there is always a slight increase over time, and values are higher under the Paris Agreement targets compliance (i.e., 2DS) comparing to the BAU. The main reason is that the avoided burdens of cleaner energy according to the energy mix of the 2DS framework report lower credits comparing to BAU (see e.g., Figures 3.4g and 3.4h for NA). Those impacts presented higher values (up to 11%, 9%, 23% and 9%, respectively) in the 2DS scenario, considering that the energy produced from FLW incineration had higher burdens than the cleaner energy that it replaces as avoided charges. Thus, for this management scenario, the compliance with the Paris Agreement targets would penalize incineration. Conversely, the incineration implementation would be reinforced in an undesired scenario of progressive increase in emissions of CO_2 associated with the energy mix until the year 2040. In comparative terms, only the regions with the presence of FLW incineration show a reduction in the consumption of abiotic resources (ADP) related to the ones in which such technology is not present. This is due to the higher energy efficiency of incineration and, therefore, the resources avoided in obtaining energy according to the energy mix projections. Furthermore, this is even more evident in the BAU framework, with a higher consumption of non-renewable resources. The remaining impacts are higher when the incineration is included within the FLW management alternatives, showing the lowest environmental burdens in the regions where AD and AC are used. This is especially remarkable when complying with the Paris Agreement targets, in which the impact is only reduced in regions without incineration plants, since FLW combustion emits a higher amount of acid gases and particles than to obtain their equivalent energy considering the mix in the 2DS scenario.

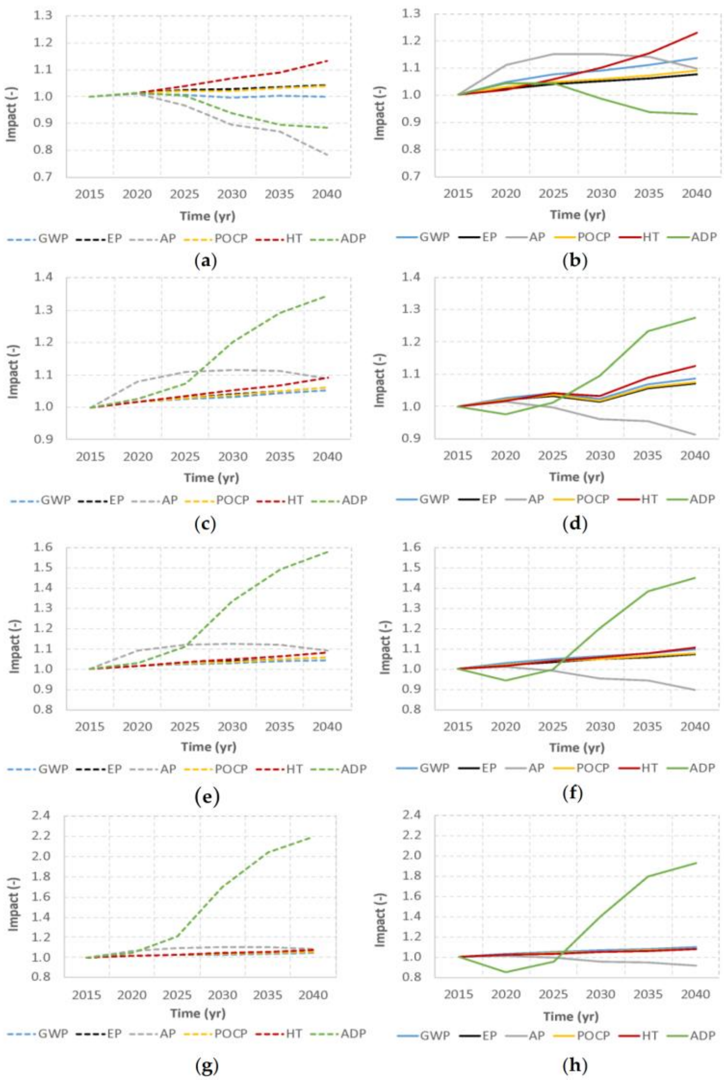

Figure 3.4 Environmental impacts of current FLW management grouped around main FLW treatment in four clusters. All impacts are normalized by their values in 2015. CT region, as representative for high incineration: (**a**) BAU, (**b**) 2DS; EX region, representative for landfilling with energy recovery: (**c**) BAU, (**d**) 2DS; VA region, representative for a mix of landfilling and AD: (**e**) BAU, (**f**) 2DS; NA region, representative for AC: (**g**) BAU, (**h**) 2DS.

Alternative simulated scenarios analysis

This section analyses the environmental performance of changing the FLW management configuration through reducing landfilling and increasing the other technologies, as introduced previously. First, the different configurations are analyzed per ton of FLW managed.

Figure 3.5 presents the results obtained for GWP, AP, EP, POCP, HT and ADP for scenarios 2-6 in the BAU and 2DS approaches (measured in kg of reference substance per ton of FLW).

In line with the results of Scenario 1 discussed in the first part of the results, incineration of organic matter, as an alternative to landfill, represents the scenario with the highest environmental burdens in terms of GWP, EP, AP and POCP, both in the BAU (Figures 3.5a, c, e, g, i, and k) and 2DS (Figures 3.5b, d, f, h, j, and l) frameworks (a comparison of S1 with the rest will be shown previously). It acquires special significance if the Paris Agreement targets are achieved, where the energy recovered results in GHG emission rates that could be three times higher until 2040 due to the displacement of clean energy. Scenario S5 (in green), which diversifies FLW treatment strategies between incineration, AC and AD; is an alternative that, from a comprehensive FLW management perspective (including the inorganic fraction) is attractive. This scenario is strongly influenced by the emissions associated with incineration, being less attractive if the management of the organic fraction is addressed alone. Concerning HT and ADP, both are negatively influenced by the presence of AC and AD in the FLW management option, respectively. This shows the existing trade-off between the different impact categories to be considered by decision-makers.

In the same line of the analysis performed in the first part of the results, Fig. 3.6 shows the regional evolution of the environmental performance in 2040 for the new FLW configurations (scenarios 2-6) in terms of GWP represented as the variation of percentage between the impact in 2040 and the impact in 2015. Both BAU and 2DS frameworks are analyzed (Figure A2.1 contains the results for the rest of the impact categories). The results show how the alternative for energy recovery (i.e., S4, incineration share 90%) worsens the GWP by up to 20% in all regions in the BAU framework. If compliance with the Paris Agreement targets is attained (i.e., 2DS), a worsening in GWP is also general for all regions, but in this case the energy recovery from FLW implies an increase in GWP of approximately 60% for AN and CM, in which the management strategy would go from landfilling to incineration, and higher than 80% for CL, in which incineration would replace landfilling and AD.

However, the latter case can only be approached as a theoretical reference, as in the other regions in which there are already management options other than landfilling, and in which its replacement in the short or medium term has no practical value.

Discarding the substitution of landfill by incineration, all the other scenarios present significant improvements compared to the current scenarios, reaching improvements through AD and AC (i.e., S6) above 60% for CL and AN in the BAU framework (above 80% in compliance with the Paris Agreement targets), higher than 40% for CM under the BAU framework (above 60% in compliance with the Paris Agreement targets), and around 20% in practically all the other regions. The analysis of the results for the rest of the impacts studied showed a similar trend, as shown in the Tables A2.2-6 in the Annexes. Consequently, decisions on investment in technologies in the future, need to be regional instead of national, and always attending to environmental and technical criteria such as those presented in this work, over simplistic and short-term political evaluations. This could be, thereby, an important path for future research on regional planning, considering other factors as the transport costs, the spatial occurrence of specific FLW generators (such as primary production or food processing and packaging industry), the regional demand (e.g., for energy, for compost), the acceptance of society (e.g., related to source-separation), the on-site demand for energy not connected to season, as well as the physical and chemical characteristics of FLW.

Comparison with the literature

AD coupled to AC, which was revealed in this study as the path with the highest reduction across all analyzed impacts (i.e., S6), has been also highlighted as an efficient alternative technology, combining biofuel production (i.e. biogas from AD) with sustainable waste management

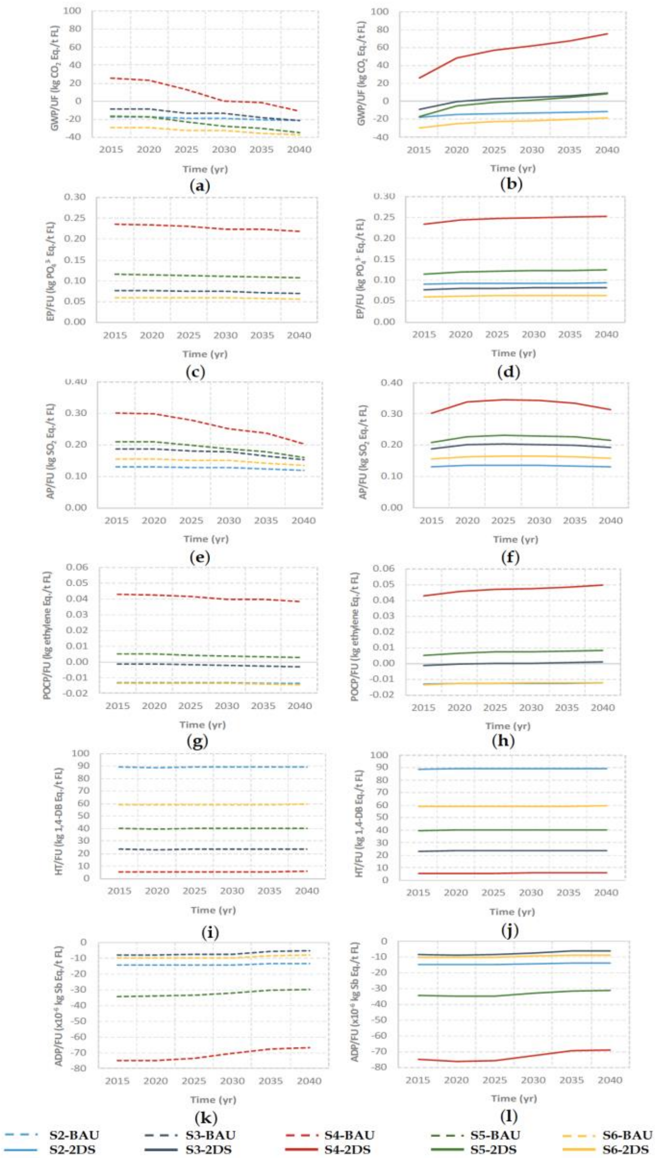

Figure 3.5 Life cycle impact assessment for the considered FLW management scenarios. Global Warming Potential (GWP): (**a**) and (**b**); Eutrophication Potential (EP): (**c**) and (**d**); Acidification Potential (AP): (**e**) and (**f**); Photochemical Ozone Creation Potential (POCP) (**g**) and (**h**); Human Toxicity (HT): (**i**) and (**j**); Abiotic Depletion Potential (ADP): (**k**) and (**l**). Figures on the left represent BAU, and on the right 2DS.

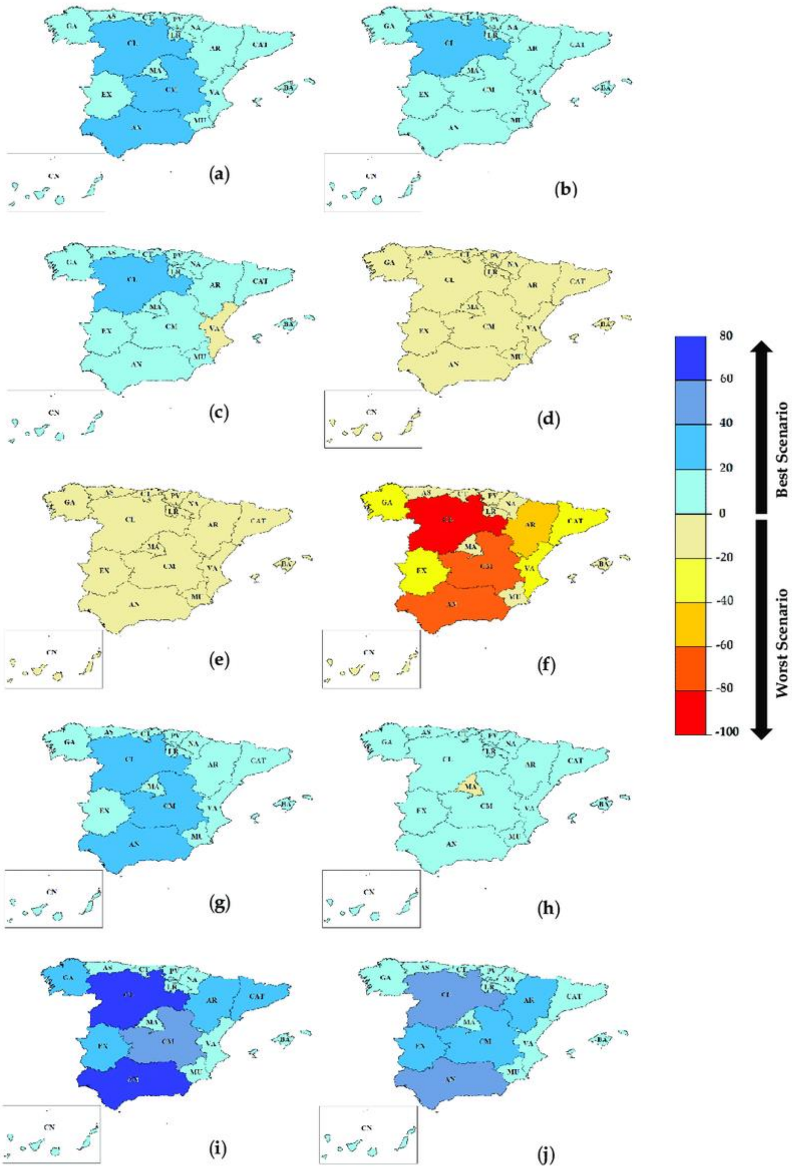

Figure 3.6 Relative variation (%) of GHG emissions as compared to the current scenario (S1) per region for the considered FLW management scenarios. Scenario S2: (**a**) BAU and (**b**) 2DS; scenario S3: (**c**) BAU and (**d**) 2DS; scenario S4: (**e**) BAU and (**f**) 2DS; scenario S5: (**g**) BAU and (**h**) 2DS; scenario S6: (**i**) BAU and (**j**) 2DS.

(Achinas et al., 2017, Xu et al., 2015), as long as the produced biogas is utilized for energy substitution (Moller et al., 2009). Different comparative studies, analyzing landfilling, incineration and AD scenarios, showed similar conclusions, highlighting AD (i.e., S3) as the most favorable alternative in terms of GWP (Evangelisti et al., 2014) and according to the Energy Return on Investment – Circular economy index, presented in Section 2.3 (Chapter 2). Moreover, a study conducted in Sweden (Bernstad and La Cour Jansen, 2011) suggested that AD with the use of biogas and digestate as substitution for vehicle fuel and chemical fertilizers, respectively, resulted in higher avoidance of GWP and POCP, compared to AC or incineration of FLW. Regarding the comparability between AD and AC, the current LCA methodology underestimates the positive impact on environment provided by compost (e.g., there is no accounting of the improved water holding capacity, improved pore volume, increased biodiversity of soil organisms or higher content of stable organic matter through use of compost). In fact, when digestate after AD processing is used, most of the carbon content is already used as methane and the quality of digestate cannot be compared to compost. Therefore, it could be assumed that the positive impact of compost is undervalued in general and in comparison, of digestate coming from AD. Thus, the environmental benefits from AD may have shown higher values. An Arcadis Report (2010) stated that a switch from landfill and incineration is favorable to both AC and AD. Moreover, it showed also that from an economic point of view in terms of treatment costs, switches to AC are more advantageous than to AD, outweighing that the environmental benefits are generally higher for AD. The AC option alone (i.e., S2), has also been presented in the literature as an environmentally friendly and sustainable alternative to manage organic solid wastes (Martínez-Blanco et al., 2010).

On another note, although in general incineration (i.e. S4) has gained a bad reputation due to certain environmental impacts, such as the emissions of acid gases, dioxins and furans (PCDD/F), as well as GHG emissions (Margallo et al., 2012), there are other comparative studies (Bang-Jensen et al., 2016, Fruergaard and Astrup, 2011) that suggest lower environmental impacts related to incineration as compared to AD coupled with AC. Regarding the diversity of conclusions for apparently similar scenarios, a review including 25 comparative LCA studies addressing FLW treated in landfills, incineration plants, AC (small and large scale) and AD (Bernstad and La Cour Jansen, 2012), suggested that the GWP results vary largely amongst the studies. Those differences could be due to the definition of the system boundaries and methodological choices or the variations in the input data, as they may not analyze only the category of organic waste, but also fractions of higher calorific waste for production of solid recovered fuels, with higher energy generation rates through incineration.

Finally, the results of the current study reinforce the general consensus in the literature by highlighting that landfilling scenarios, with and without energy recovery, are those that present the highest environmental impacts (Burnley et al., 2011). Hence, regions that still orient their waste management policy towards landfilling are those with the highest potential for the development of novel waste management policies calling for a reduction in the quantity of biodegradable waste landfilled (BOE, 2020).

3.2.4 Conclusions

The management of FLW in Spain is highly regionalized, and presents as many scenarios as regions and treatment models associated. In this context, it is not possible to define from the technological and environmental point of view a single common centralized strategy for the entire management of FLW in Spain, beyond establishing harmonized guidelines and criteria that facilitate both the transition to a circular economy and reducing environmental impacts, especially those associated with global warming.

Results highlighted how the alternative for energy recovery worsens the GWP in all regions in the BAU and 2DS frameworks by up to 20% and between 60-80%, respectively. All the other scenarios presented significant improvements (20-60% in BAU and 20-80% in 2DS frameworks) compared to the current scenarios. Thus, the regionalization of FLW management strategies is corroborated in this study as a way forward in upcoming decades, which should be transcribed in an increasingly regional decision-making capacity for policy-makers, focusing firstly on regional criteria and characteristics of the FLW management systems than on national plans seeking uniformity of strategies.

Despite the importance of achieving compliance with the EU landfill reduction targets, in general terms, landfilling with energy recovery is the most used technology in Spain with an average of 71%, and reaching for some regions up to 100% of FLW management. Promoting this technology, however, both in a 2DS and BAU framework, would increase the environmental impacts in the short and medium term, including GHG emissions by 15%, while the consumption of resources would increase significantly, not complying with the principles of circular economy. Only those regions in which incineration has a strong presence showed savings in the consumption of resources, although their contribution to global warming under 2DS is higher, as the energy obtained in incineration is not as clean as the one it replaces based on the consumption of non-fossil resources. The results obtained from the scenarios simulated concluded that, on average, those scenarios that include AD and to a lesser extent AC, have the lowest impacts, including GHG emissions. Therefore, they comply with the principles of the circular economy and are, also, the most sustainable option from an environmental point of view. In this general context, it is necessary to promote strategies conductive to the source-separated and selective collection of FLW. Nevertheless, for developing decision-making processes for each region, not only an environmental assessment, but also a socio-economic evaluation is needed. These complementary studies would help guarantee the competitiveness of novel strategies, which could be driven by new financial support derived from sources such as the EC recently presented F2F Strategy or the future CAP 2021-2027. For instance, certain variables, such as previous and future investment in waste infrastructure, maintenance of the installations and transport distances of FLW, may be decisive when thinking on developing or not potential new strategies of FLW management.

Overall, the results of this study reinforced the increasingly promoted claim that FLW is a valuable resource that should not end up in landfills, although prevention and valorization should be prioritized over any other management option, in order to move towards a circular economy in the food sector and, thus, contribute to the mitigation of climate change and other environmental impacts.

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3.3. Water footprint assessment for best-regionalized strategies for food loss and waste management in Spain

3.3.1 Introduction

The availability of freshwater is one of the biggest limitations and challenges on food production, as it is an increasingly scarce and overexploited resource in many parts of the world (Ridoutt et al., 2010). Moreover, freshwater and food access are far from being guaranteed for a substantial part of the world's population (Shukla et al., 2019). Assuming that freshwater is a limited resource, the concept of water footprint (WF) has gained increasing interest in recent years (Aivazidou et al., 2016). As described by Quinteiro et al. (2014), this concept was first proposed by the quantification of virtual water flows between nations in relation to the international crop trade, presented by Hoekstra and Hung (2002). Subsequently, it was described in greater detail in the WF calculation for each nation worldwide presented by Chapagain and Hoekstra (2004), in the worldwide WF of cotton consumption developed by Chapagain et al. (2006), and in the WF assessment manual created by Hoekstra et al. (2011). This WF method quantifies both direct and indirect volumetric freshwater use and pollution along supply chains, looking not only at the direct water use of a consumer or producer, but also at the indirect water use (Chapagain and James, 2013). According to Hoekstra et al. (2011), the WF of a product comprises three color-coded components: i) green water (i.e., water evaporated from soil moisture supplemented by rainfall), blue water (i.e., water withdrawn from ground or surface water sources), and grey water (i.e., water quality impairment).

More recently, a novel WF assessment framework has been developed and summarized in the ISO 14046 (2014), in order to assess both quantitative and qualitative water-related impacts, from a life cycle perspective, and encompassing freshwater scarcity (water consumption) and water quality degradation. Following ISO recommendations, in order to overcome the lack of a consensual assessment method related to the most critical and controversial pillar of WF – quantifying water scarcity-, and following the recommendation of the UNEP/SETAC Life Cycle Initiative, the Available Water Remaining (AWARE) method has arisen (Boulay et al., 2018). It has been the first assessment method destined at estimating the impact of the removal of a certain quantity of blue freshwater from its natural systems, i.e., the relative availability of water remaining per area in a watershed, after the demands of humans and aquatic ecosystems have been met (Bizarro et al., 2018). The LCA-based WF impact methodology has progressed rapidly, being the WF of a product the sum of all the water consumed across its entire value chain (Blas et al., 2018). It is composed of a set of methods for addressing different freshwater types and sources, pathways and characterization models with different spatial and temporal scales (Caldeira et al., 2018).

In this regard, food and in particular agri-food products have a great demand for water (Caldeira et al., 2018), being the sector increasingly analyzed by many WF studies globally (Bong et al., 2018). In this sense, Mekonnen and Gebens-Leenes (Mekonnen and Gebens-Leenes, 2020) highlighted the fact that global studies which estimated the global consumptive (green plus blue) WF of crop production range from 5,938 to 8,508 km^3/year. They explained that the existing differences in the WF estimates in the literature can be assumed to be due to differences in the modeling approach, input data, including climate and cultivated area, the number of crops and their specification, and the methods used. As presented by Quinteiro et al. (2014), different scientific methods have been developed to assess the impacts related to freshwater as an integral part of the LCA methodology, which have also been applied to a wired range of agricultural and agro-industrial products such as pasta sauce and peanuts (Ridoutt et al., 2009), broccoli (I Canals et al., 2010), asparagus and tomato (Frischknecht et al., 2006), among others. Due to the relatively recent development of these methods, the LCA community has been recommending their application in case studies of food products in order to understand the individual significance of each one (Kounina et al., 2013). For instance, it has been estimated a worldwide average WF of 40 l per slice of bread, 74 l per 250 ml of beer, 2,497 l per kg of rice, and 3,178 l per kg of hard cheese (WFN, 2010). More specifically, Karandish et al. (2020) studied the green, blue and grey WF associated with the production of wheat, barley and rice, and the resulting water scarcity and pollution levels at the provincial scale in Iran. The results suggested that both total WF and its blue water share have increased considerably since 1980.

In this context, Spain is the most arid country in the EU, but also one of the main producers of agri-food products, many of which are exported to other EU nations. Consequently, the management of water resources in Spain is an important and controversial issue (Chapagain and James, 2013). According to Chapagain and Hoekstra (2004), total water requirements in Spain (green and blue) by the different economic sectors are about 100 km^3/year, 80% of which can be directly attributed to the agricultural sector. Different studies have already analyzed the WF within different topics in the field of the FSC in Spain. Among them, López-Gunn et al. (2012) addressed the WF linked to shifts from recommended diets. In 2014, Duarte et al. (2014) studied the evolution of domestic water consumption as a consequence of increasing agricultural production, as well as the impact that the increasing need for water had on the construction of infrastructure for irrigation, examining the water consumed in the production of vegetable and animal goods between 1860 and 2010. In 2018, Villanueva-Rey et al. (2018) analyzed the WF profile of grapes used in the vinification process in the Ribeiro appellation, for the period 2000-2009. In that same year, Blas et al. (2018) assessed the water implications within and beyond Spanish territory, focusing the study on food consumption and waste in Spanish households, and grouping total food into 10 different food groups.

In this framework, when food is wasted, embedded water and energy used to grow and process crops and other food products are also wasted. Moreover, greenhouse gas emissions are emitted, and a wide range of other environmental impacts (e.g., toxicity-related impacts, eutrophication…) are generated. The quantification of water and other environmental impacts of food and drink waste is of great potential interest, and WF is a useful tool for linking water resource use to food production (Vanham et al., 2013). Within food production and consumption, FLW generation has become a central concern in the social and political debate, as at least one-third of all edible food production is wasted worldwide throughout the entire FSC (20% in the EU) (Gustavsson et al., 2011). A few studies have already studied the WF of FLW generation in some stages of the FSC in certain countries, as is the case of the work developed by Zero Waste Scotland (2011), which estimated the WF of avoidable food waste representing nearly 6% of all of Scotland´s water requirements. Ridoutt et al. (2010) assessed the WF of FLW of fresh mango in Australia, suggesting that interventions to reduce FLW will have an important impact in terms of freshwater resource availability. Currently, an important fraction of FLW in Spain is still landfilled, whereas the remaining fraction is managed either in the 10 existing incineration plants, or in mechanical-biological treatment stations, based on AC or AD systems (PEMAR, 2015).

In this line, although certain studies have already assessed WF impacts regarding some stages or products of the FSC, as far as we were able to ascertain, there is no study assessing the influence of FLW generation along the whole FSC, and the different FLW management options regarding its WF. As previously highlighted, the best FLW management strategies for each Spanish region from an environmental point of view can vary considerably. This study aims to include a WF approach to the decision-making process on FLW management in Spain, regarding the 17 regions. All it, from 2015 until 2040 in a framework of (i) compliance with the goal of limiting global warming to well below 2°C above pre-industrial levels and pursuing efforts to limit it to 1.5°C (2DS) and (ii) non-compliance with the Paris Agreement targets - Business as Usual (BAU). Thereby, the quantification of water and different environmental footprints (developed in Section 3.2) in the regions of Spain, would be linked. This strategy has been suggested by previous studies, as food and drink waste is of great potential interest to a range of stakeholders such as consumers, food retailers, suppliers and producers, NGO, environmental agencies, water management policy groups, national and regional governments (Zero Waste Scotland, 2011). The benefits of this perspective aim to complete and reinforce the thesis of the need of developing regionalized FLW management policies in Spain, moving from national to regional approaches when developing future roadmaps.

3.3.2 Methods

Goal, function, and functional unit definition

This study conducted an WF assessment based on the ISO 14046 (2014), and is linked to Section 3.2, where it has been developed an LCA methodology regarding other environmental impacts. It is aimed to compare the results for determining the most optimal scenario of FLW management for each of the 17 regions in Spain (as shown in Figure 3.7). The current FLW management in each region (S1) was compared to five alternative scenarios (S2-6) simulating different potential FLW management situations (as explained in Section 3.2). The environmental performance of these scenarios was evaluated for the period 2015–2040 considering the compliance (2DS) and non-compliance (BAU) with the Paris Agreement targets. In order to develop the simulations over time, the energy mix projections developed by the TIMES Integrated Assessment Model from the University College London (TIAM-UCL), have been used. This model considers 16 regions covering all the world (Anandarajah et al., 2011). In this case, data for Western Europe, which includes Spain, were used. The energy used and generated for the energy mix, are linked to environmental impacts and avoided burdens, respectively. The main function of the system is the management of FLW under different simulated scenarios. In order to measure this function, a suitable functional unit was defined, to which all the inputs and outputs were referred. In this case, the functional unit has been assumed as the treatment of one metric ton of FLW in each Spanish region in 2015.

System boundaries

As seen in Figure 3.7, this WF assessment includes within the system boundaries food loss generation in the first stages of the FSC - agricultural production, processing and packaging -, and food waste in the distribution, and consumption stages, as well as the FLW management. FLW has been separated into 11 fractions, following the division suggested by FAOSTAT (FAO, 2014), considering cereals, sweets, vegetable oils, vegetables, fruits, pulses, roots, dairy products, eggs, fish and seafood, and meat. Similar WF loads of FLW collection and transportation were assumed for all management options, due to their low influence. The mass balances from Section 2.2 (Chapter 2) were used, and the calculated FLW management percentages were those shown in Section 2.3 (Chapter 2). Due to their low demographic weight (< 0.4%), the autonomous cities of Ceuta and Melilla, two exclaves situated in the north of Africa, were left out of the scope of the study.

Description of scenarios under study

Six scenarios, including the current situation in 2015 (S1), have been analyzed within this WF assessment by implementing them in the 17 regions.

- Scenario 1 (S1). The baseline scenario, which considers the current (i.e., using 2015 as the year of reference) FLW management in each region, based on data published by the Spanish Waste Management Framework Plan (PEMAR, 2015) and the CONAMA Foundation (CONAMA, 2014).
- Scenario 2 (S2). It is based on the FLW management framework in Germany, with AC representing the highest part of the treatment. Moreover, AD systems are increasingly being promoted (DBFZ, 2017). In this line, it is considered that 75% of FLW is going to an AC plant, 20% to AD and the rest is divided between landfill (2.5%) and incineration (2.5%) facilities.
- Scenario 3 (S3). The use of AD systems is prioritized, considering that 75% goes to AD, 20% to AC, and the rest is divided between landfill (2.5%) and incineration (2.5%).
- Scenario 4 (S4). It is based on current Danish conditions, where over 90% of the share of bio-waste is incinerated (Bang-Jensen et al., 2016). Thus, 90% of FLW goes to incineration, while the remaining 10% is equally distributed between landfilling, AD and AC.
- Scenario 5 (S5). This scenario is based on the increasingly promoted claim that FLW is a valuable resource that should never end up in landfilling sites (Vision 2020, 2013). It is assumed that landfilling is not a FLW management alternative, so 33.3% goes to each of the remaining management options (i.e., incineration, AC and AD).
- Scenario 6 (S6). Landfilling and incineration are not considered in this scenario, so 50% of FLW is treated in AC, and 50% in AD. The fact of excluding incineration plants in S6 refers to the fact, that similarly to what has recently occurred to coal plants in many nations including Spain, they will potentially have problems to provide energy to the system by the year 2030. More specifically, they will have serious

difficulties to maintain competitiveness against other technologies in an environment highly conditioned by the European response to climate change, in which the cost of CO_2 will tend to be increasingly higher (IDAE, 2020.

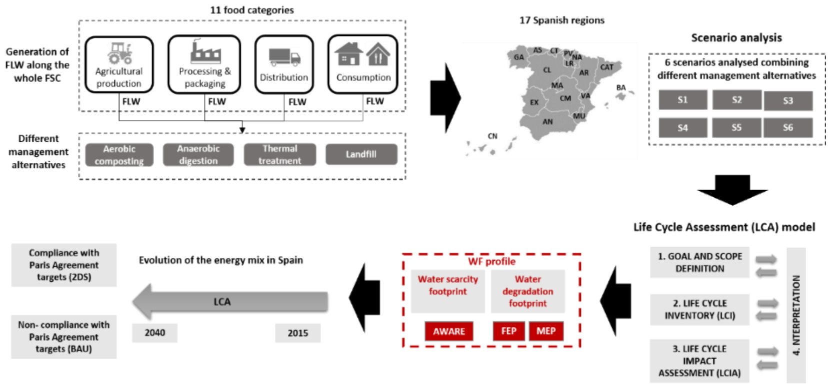

Figure 3.7. Conceptual diagram of the Life cycle assessment methodology developed, linked to the water footprint assessment (in red). Regions: AN: Andalusia; AR: Aragon; AS: Principality of Asturias; BA: Balearic Islands; CN: Canary Islands; CT: Cantabria; CM: Castile-La Mancha; CL: Castile and Leon; CAT: Catalonia; EX: Extremadura; GA: Galicia; LR: La Rioja; MA: Community of Madrid; MU: Region of Murcia; NA: Chartered Community of Navarra; PV: Basque Country; VA: Valencian Community; FSC: food supply chain; FLW: food loss and waste; ISO: International Organization for Standardization; FE: Freshwater eutrophication; ME: Marine eutrophication; S1(BS): Scenario 1 (Baseline Scenario); S2: Scenario 2; S3: Scenario 3; S4: Scenario 4; S5: Scenario 5; S6: Scenario 6; 2DS: compliance with the Paris Agreement targets; BAU: non-compliance with the Paris Agreement targets; Thermal treatment: incineration.

Table 3.5 describes the simulations (S2-6), and Table 3.6 shows the assumed distribution of treatment of FLW in all the Spanish regions (S1). It is remarkable the fact that in the regions of CM, EX and the Region of Murcia (MU), the 100% of the FLW goes to landfill. In the region of Andalusia (AN), a 93.8% is landfilled. On the other hand, in Balearic Islands (BA) and Cantabria (CT), a higher fraction goes to thermal treatment plants (72.7% and 64.9%, respectively).

Table 3.5. Simulated scenarios of FLW management in Spanish regions. Scenarios S2 to S6 comply with the Directive 1999/31/EC on waste landfilling (EC, 1999).

Scenarios	Landfill	Incineration	AD	AC
S1	Dependent on each region (see Table 2)			
S2	2.5%	2.5%	20%	75%
S3	2.5%	2.5%	75%	20%
S4	3.3%	90%	3.3%	3.3%
S5	-	33.3%	33.3%	33.3%
S6	-	-	50%	50%

Life cycle model

The life cycle model described in Figure 3.8 includes the generation of FLW in all the considered FSC stages: agricultural production, processing and packaging, distribution and consumption. The management of these FLW was modelled based on the Ecoinvent database (2016) and the professional database of GaBi (2019). The input and output flows of the unit processes were modified in order to consider the regionalized water requirements and effluents in Spain. FLW management considers the alternatives of AC, AD, incineration and landfill:

- AC was modelled using the professional database of the GaBi software (2019). It considers closed halls or so-called composting boxes or rotting tunnels. The input waste is assumed as an average mixture of biodegradable waste consisting of biodegradable garden and park waste, as well as a 35% content of food and kitchen waste. For the selective collection fraction, the composting system includes the energy requirements of a mechanical separation unit (Cimpan and Wenzel, 2013).
- AD was modelled using the Ecoinvent database (2016), including storage of the substrates, anaerobic fermentation, as well as the storage of digestate after fermentation. One cubic meter of biogas is assumed to produce 2.07 kWh of electricity (Junta de Andalucía, 2011).
- Incineration was based on the professional database of the GaBi software (GaBi, 2019) for the biodegradable waste fraction of MSW. To

model a single fraction, energy production and credits 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 plants in Spain (Margallo et al., 2014). The incineration of one metric ton of waste produces 495 MJ of energy, 1,277 MJ of steam, 220 kg of bottom ash, and 42 kg of boiler ash, filter cake and slurries.

- Landfill with biogas recovery, includes biogas and leachate treatment and deposition. Sealing materials (e.g., clay or mineral coating) and diesel for the compactor were also included. The modelling was based on the landfill process for municipal household waste from the professional database of GaBi (2019). According to the model, 17% of the biogas naturally released is 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 FLW was assumed (GaBi, 2019).

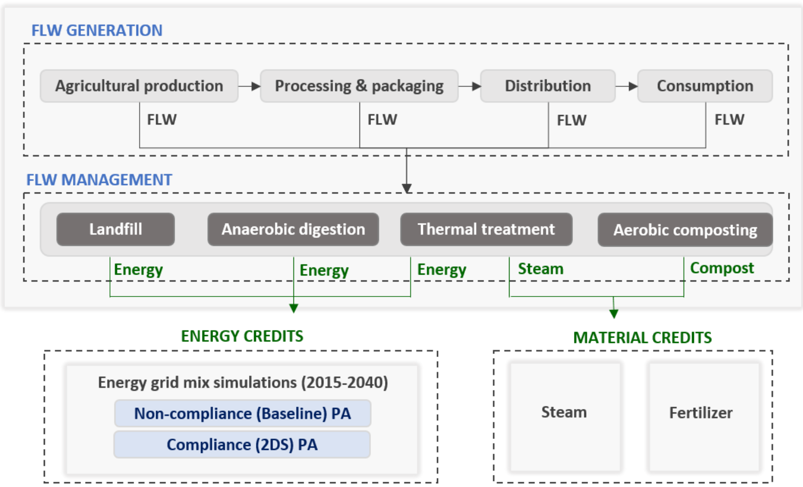

Figure 3.8. Graphical representation of the system boundaries and life cycle modelling of the water footprint FLW management strategies. PA: Paris Agreement targets.

Table 3.6 Percentage of FLW by treatment and region in 2015. Data represented in percentages calculated from mass balances in metric tons reported for each region. Regions: AN: Andalusia; AR: Aragon; AS: Principality of Asturias; BA: Balearic Islands; CN: Canary Islands; CT: Cantabria; CM: Castile-La Mancha; CL: Castile and Leon; CAT: Catalonia; EX: Extremadura; GA: Galicia; LR: La Rioja; MA: Community of Madrid; MU: Region of Murcia; NA: Chartered Community of Navarra; PV: Basque Country; VA: Valencian Community; SP: Spain.

Region	Landfill	Incineration	AD	AC
AN	93.8%	-	2.3%	3.9%
AR	62.0%	-	3.0%	-
AS	92.1%	-	-	7.9%
BA	18.9%	72.7%	5.1%	3.3%
CN	95.7%	-	4.3%	-
CT	35.1%	64.9%	-	-
CM	100%	-	-	-
CL	56.4%	-	43.6%	-
CAT	49.4%	18.4%	15.7%	16.5%
EX	100%	-	-	-
GA	33.6%	50.6%	14.9%	0.9%
LR	35.1%	-	64.9%	-
MA	63.4%	10.6%	25.5%	0.5%
MU	100%	-	-	-
NA	61.4%	-	26.6%	12.1%
PV	65.9%	25.3%	6.7%	2.1%
VA	75.9%	-	21.6%	2.5%
SP	**68.8%**	**11.9%**	**14.9%**	**4.5%**

The function of the system is to treat FLW; thus, all the treatments were compared in the same terms. However, all the management alternatives are multifunctional processes, adding an extra function to the system. Energy is recovered from AD, landfilling and incineration, which also produces steam. In the case of composting material credits are obtained from the use of compost as fertilizer. In these multifunctional systems, the environmental burdens associated with a particular process must be partitioned over the various functional flows of that process (ISO 14044). To handle these processes, the ISO 14044 proposes as a first solution to expand the system boundaries or divide the process into sub processes (ISO 14044). In this case, additional functions (generation of energy, steam and compost) have been substracted from the system in terms of production of electricity, or the generation of steam and fertilizer. The avoided burden for electricity is based on the electricity mix simulations according to the TIAM-UCL model. As shown in Section 3.2, the evolution in a BAU framework suggests continuous increase in the energy produced from coal, reaching by 2040 around 60% of the total energy generation, followed by hydropower (20%), and natural gas, with less than 10%. Biomass and biomass with carbon capture sequestration will begin to decrease starting in 2025 until almost disappearing by 2040. Regarding the evolution in a 2DS framework, surprisingly, nuclear power seems to have a significant increase, reaching 55% of the total electricity mix in 2040, followed by hydropower (20%) and onshore wind (10%). Decarbonization policies in the electricity sector may foster the rise of a controversial energy source (i.e., nuclear), which opens the debate on whether the outcome justifies any strategy to meet the Paris Agreement targets. This fact, suggested another policy advice, which would be complementary and necessary together with climate policies. Finally, both options suggested a reduction of the energy generated by biomass in 2025, which nearly disappears by 2040.

Due to the construction of this model, the avoided loads from energy represent a reduction in the environmental impacts associated with the mix of each year. This implies that if the energy mix evolves towards cleaner energy sources, as in the 2DS situation, the avoided loads lose importance since the impacts generated are less. If the energy mix does not evolve towards cleaner energy sources (as in the BAU situation), the avoided loads have a greater effect. These avoided burdens will have influence on the WF, since there is clear link between energy and water consumption. According to Mesfin et al. (2015) the global WF of electricity and heat is estimated to be 378 billion m^3 per year, leading the water demand biomass and hydropower.

Life cycle inventory

A set of assumptions and calculations were carried out to develop the life cycle inventory (LCI) of FLW generation and management in each region regarding the four stages of the FSC, and the 11 FLW categories. It was assumed that FLW accounts for 49% from total reported waste (CONAMA, 2014). The percentage of assumed FLW was implemented to a set of data reported by the Spanish Ministry of Agriculture, Fishery and Food (Mesfin, 2015, MAPA, 2019), in order to determine the percentage of livestock, agricultural or fishery production, as well as the number of existing industries, in each region, from the total values reported. Thereby, FLW generation in the agricultural production and processing and packaging stages was calculated for each region. Regarding the distribution and household stages, the percentage of FLW assumed was implemented in the existing population in 2015 (MAPA, 2017) adding as a part of the population the number of tourists in each region in that year (INE, 2016). In order to calculate the fractions of FLW going to each of the four different management options considered, data from the Spanish Ministry for the Ecological Transition and the Demographic Challenge (2015), as well as from the CONAMA (2014), were used. The same percentage of considered FLW (49%) was considered from the total waste generation data.

Water footprint profile

A WF assessment can be represented by the WF indicator or by the WF profile. The former is related to one single impact category, that is water scarcity. On the other hand, according to the ISO 14046 (2014), the WF profile includes the water scarcity footprint (i.e., impacts related to freshwater consumption) and water degradation footprint (i.e., impacts due to freshwater and marine water degradation). The current study determines the WF profile of FLW management, evaluating firstly the water scarcity footprint using the AWARE method (2018). This method develops scarcity indicators that are used as midpoint characterization factors (CFs) for water consumption in life cycle impact assessment. AWARE CFs determine the water availability minus the demand of humans and environmental water requirements. CFs in AWARE range from 0.1 to 100 depending on regional watershed conditions in different parts of the world, or average national values. In this study, the input and output water flows were regionalized to the Spanish situation. In contrast, according to Boulay et al. (2018) impacts due to freshwater degradation were assessed through the freshwater (FE) and marine eutrophication (ME) impact categories from the ReCiPe method (Goedkoop et al., 2008). In order to compare the scenarios, a weighting process was done, by considering the same importance to each of the factors.

Table 3.7 shows the WF profile for the FLW management options and Figure 3.9 the evolution of the energy mix from 2015 until 2040 in a BAU and 2DS situations.

Table 3.7. Characterization factors (CFs) used regarding the four management options considered in the study.

Impact category	Landfill	Incineration		AD	AC	
		Incineration	Process steam		Composting	Ammonium sulphate
ReCiPe 2016 v1.1 Midpoint (E) - Freshwater Eutrophication [kg P eq.]	3.00E-03	6.25E-06	-2.02E-06	2.00E-04	4.75E-05	-5.78E-05
ReCiPe 2016 v1.1 Midpoint (E) - Marine Eutrophication [kg N eq.]	7.70E-03	1.00E-03	-2.52E-05	1.76E-05	2.00E-04	-2.80E-03
AWARE, upper characterization factor for unspecified water [m³ world eq.]	3.14	254.41	-13.40	9.15E-02	23.67	2.33

Negatives values are obtained in AWARE and ReCiPe indicators for the energy and material credits in incineration (steam and energy), landfilling (energy), AD (energy) and composting (fertilizer). Only for the AWARE method the avoided burden of ammonium sulphate is positive. In this method, CFs for water inputs (river, lake and ground water requirements) are positive and negatives for water outputs (emissions to fresh water). So, the AWARE indicator calculates the impact of the inputs less the outputs. This means that if the absolute value of indicator is positive then the avoided burden is negative, because it is considered as an environmental benefit. In the case of ammonium sulphate the absolute value is negative and then the avoided burden is positive. This means that in this process the impact linked to water emissions is higher than the impact from the water demand.

As represented in Figure 3.9, Fresh and Marine Eutrophication show a similar trend for the energy mix, decreasing from 2015 to 2040 in the BAU and 2DS approximations. Biomass has the highest influence on the mix´s impact (85% on average in marine and 95% in freshwater), which experienced a decrease of around 43% in both indicators for 2040. However, the indicators raised in 2020 for the 2DS situation due to an increase of 35% in the biomass impact. On the other hand, for the AWARE method the amount of water of the energy mix increased with the time. Hydropower energy represents more than 79% of the impact, which increased a 72% in 2DS and a 44% in BAU situation.

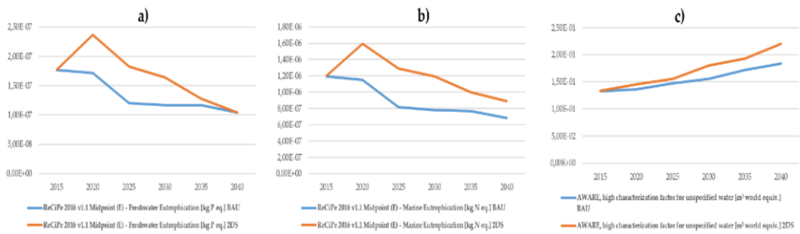

Figure 3.9. Evolution of the characterization factors used for the water footprint profile assessment, being a) Freshwater Eutrophication [kg P eq.], b) Marine Eutrophication [kg N eq.], and c) AWARE [m^3 world eq.].

Main limitations and assumptions of the study

The main limitation of the present study is the data uncertainty regarding the amount of FLW and the type of management for the different FLW categories in the reference year. The amount of FLW also depends on factors such as the time of the year and the region. Moreover, as the whole process of FLW generation and management takes time and in the meantime a fraction of the mass might be lost (e.g., due to drying), it is difficult to couple them. Differences may also happen due to waste import and export flows, as well as unaccounted fractions. Although information could be found explaining the different treatment and disposal methods, data available refer to the generation of biodegradable municipal waste, not to the generation of bio-waste or FLW (Arcadis, 2010). Additionally, biodegradable municipal waste includes paper, cardboard and biodegradable textiles and, in the more advanced stages of the FSC, FLW is usually mixed with general waste. All these uncertainties complicate the determination of the percentage that corresponds to FLW exclusively (Bernstad Saraiva et al., 2017).

This study has applied an attributional approach in which the electricity produced within the system boundaries is sent to the national grid and, thus, the system is credited with the WF impacts of producing that amount of electricity using average data from the electricity mix. The selection of a consequential approach would have identified the marginal technology from the mix displaced by the energy produced within the system boundaries and thus, the system would be credited with the impacts of producing that amount of electricity using that displaced technology. The selection of one approach or the other could have an important effect on results and conclusions drawn from LCA for solid waste management systems (Vázquez-Rowe et al., 2021). Moreover, technological developments related to the FLW management methods, such as improving the electricity production efficiency or cleaning exhaust gas technology, were not considered in this analysis.

Another potential source of uncertainty is the fact that the evolution of FLW generation until 2040 was firstly considered using a logarithmic regression based on the projection of the World Bank Group (2018) regarding the Spanish population growth. Thereby, a progressive and cumulative increase was assumed, reaching 6.7% in 2040 compared to 2015. This process was omitted from the modelled methodology, since this increase did not generate changes in the scenario simulation models. For the same reason, the SDG 12.3 target, aiming to reduce food waste until 2030 by 50%, which was an important reason for recent EU legislation which set an obligation for EU member states to measure and report food waste along the FSC from 2020 onwards (EC, 2019), was not included in the modelling process.

From an impact assessment perspective, only the upper value of the AWARE CFs were used. Considering that water stress varies significantly between different areas of Spain, it could be argued that some regions of northern Spain could have been analyzed using lower CFs, understanding the local availability of water resources, requirements for human consumption, economy and ecosystem resilience and pressure.

3.3.3 Results and discussion

Water scarcity footprint

The results in the different scenarios (S2-S6) do not improved regarding Scenario 1. Moreover, the water scarcity indicator did not vary or gets a worst result in many of the regions and scenarios, highlighting the S6, where it is suggested a zero influence in regard to the currently situation. Nevertheless, Scenarios S4 and S5 are those that stand out for having the worst water scarcity footprint: S4 is dominated by incineration, whereas in S5 one third of the management is performed by incineration. Therefore, it is evident that the worst management option in terms of water scarcity is incineration. This can be explained due to the high quantity of water use for the steam process. In both S4 and S5, the regions that stand out as most affected by these supposed scenarios are CL, AN and CM.

Although in general the 2DS scenarios present slightly worse values, a difference is only seen in the case of AN, for which the 2DS situation would mean a worse water scarcity footprint in an S4 Scenario. This is due to the fact that the energy mixes are included as an avoided burden, in a context in which the rates of clean energy are higher. Thereby, the effect of the avoided burdens is lower in a 2DS framework, as there is less water scarcity generated through energy production. The results computed suggest that S6 is the best-performing scenario, followed by S3 and S2. The only regions showing a slightly higher impact are CL and AN in the case of S3, and CL in the case of S2. This implies that a mixed scenario formed by AD and AC would be the most suitable option, followed by a scenario dominated by AD.

Water degradation footprint

Figure 3.10 shows the results linked to the water degradation footprint for scenarios S2, S3, S4, S5 and S6 in the BAU and 2DS situation. Although, in general the 2DS scenarios had slightly worse values than BAU modelling, there is no significant difference between the two situations for scenarios S2, S4, S5 and S6. For the S5, only the regions of CL and CM displayed a slightly worst performance in the 2DS situation. On the other hand, in S3 water degradation decreased for the 2DS approach in most of the regions, except for MU.

In general terms, in the BAU situation, S3 (75% AD and 20% AC) showed the worst results, whereas in the 2DS approach, S4 (90% incineration) provided the highest water degradation, being in that situation S3 the best option. Thus, the evolution of the energy mix will influence the impact of AD and incineration technologies.

By regions, AN (94% landfilling), CL (56.4% landfilling and 43.6% AD) and CM (100% landfilling) had the greatest water degradation footprint which is related to high landfilling rates.

For AS (92.1% landfilling and 7.9% AC), CT (35.1% landfilling and 64.9% incineration), PV (65.9% landfilling, 25.3% incineration, 6.7% AD and 2.1%AC), LR (35.1% landfilling and 64.9%), NA (61.4% landfilling, 26.6% AD and 12.1%AC), BA (18.9% landfilling, 72.7% incineration, 5.1% AD and 3.3%AC) and CN (95.7% landfilling and 4.3% AD) a similar result was obtained in the different scenarios for BAU and 2DS approaches. The regions of the North of Spain and the islands have the lowest water scarcity and degradation, being less influenced by the type of FLW management and with the compliance of the PA targets.

Comparison with previous studies

Results of a previous study by Hoehn et al. [30] highlighted how the thermal treatment alternative worsens global warming in all regions in the BAU and 2DS frameworks by up to 20%, and between 60% and 80%, respectively. These values coincide to a great extent with the results of the current study in terms of water scarcity and of water degradation in a 2DS framework. All the other scenarios presented significant improvements (20–60% in BAU and 20–80% in 2DS frameworks) compared to the current scenarios. Moreover, the water scarcity reinforces the thesis of a better environmental performance in those scenarios that include AD and to a lesser extent AC. The fact of highlighting AD and AC as FLW management options with a lower water consumption has also been cited in the literature in a study of Lundie and Peters (2005) where home composting (10 l/FU) and centralized composting (19 l/FU) presented much less water consumption in comparison to codisposal of FLW with municipal waste (2,335 l/FU). In that research, anaerobic digestion was included in one of the two modalities of home composting. Moreover, they highlighted that centralized composting could be considered a temporary solution to educate households to separate

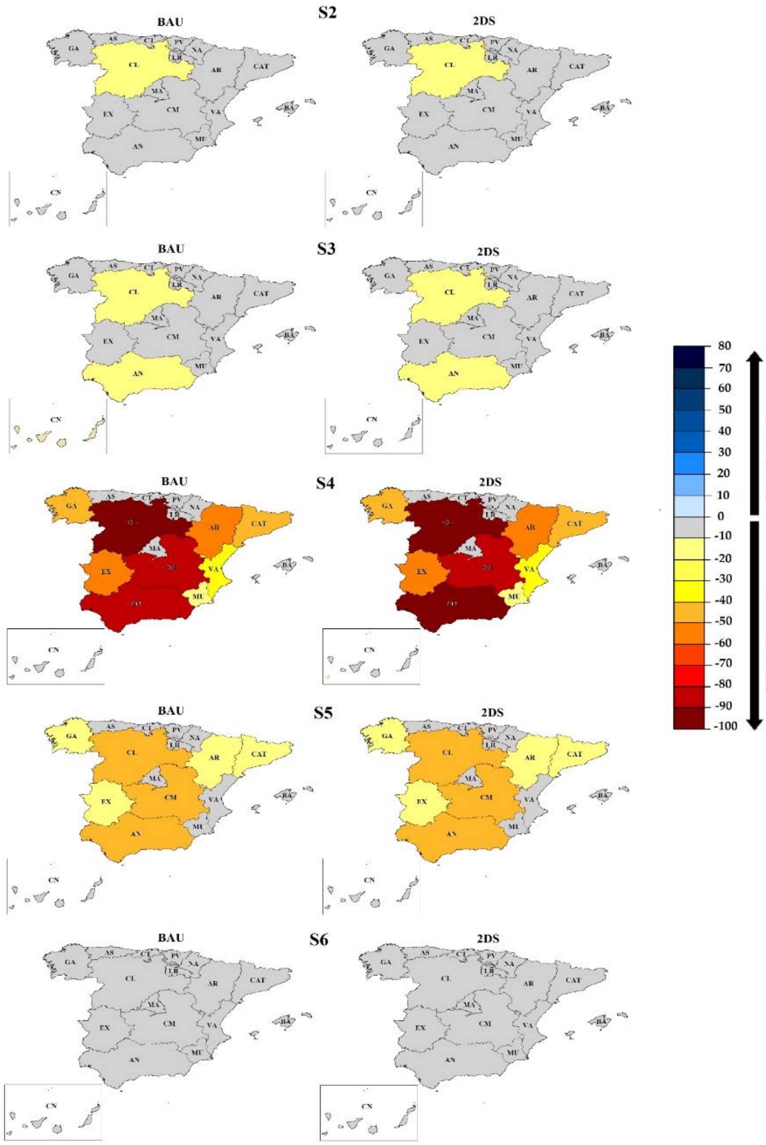

Figure 3.10. Relative variation (%) of water scarcity as compared to the current scenario (S1) per region for the considered FLW management scenarios. (**a**) BAU and (**b**) 2DS.

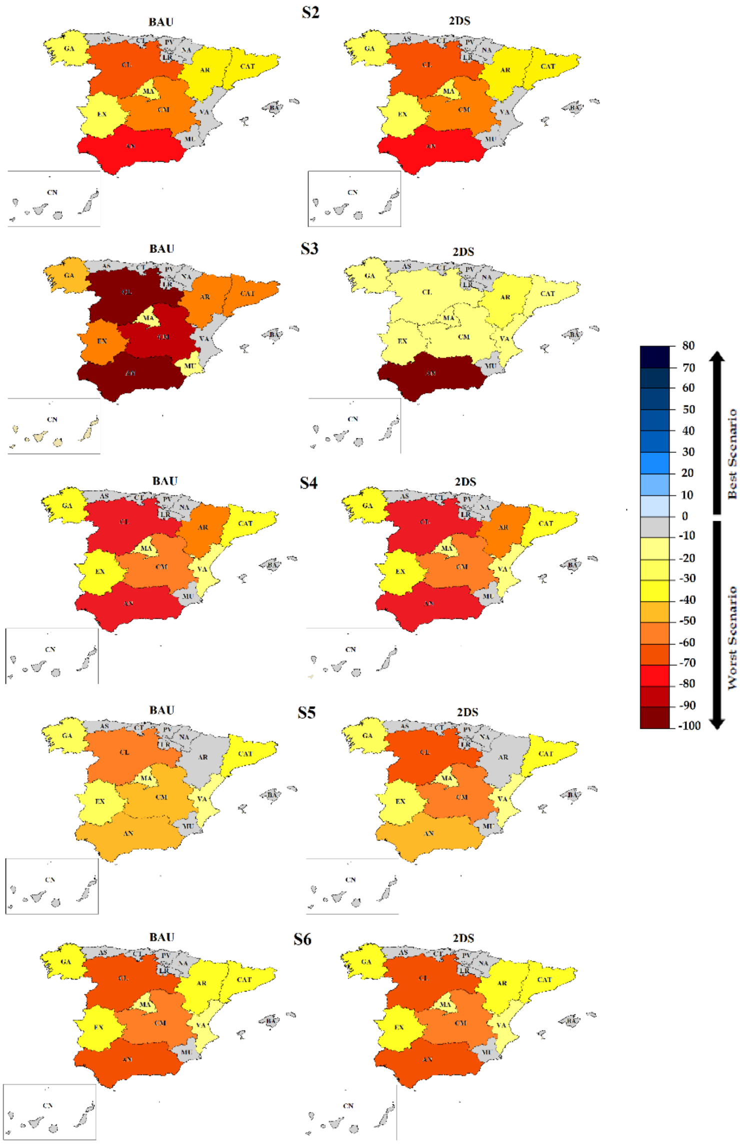

Figure 3.11. Relative variation (%) of water degradation as compared to the current scenario (S1) per region for the considered FLW management scenarios. (**a**) BAU and (**b**) 2DS.

biodegradable waste at the source before this fraction will be anaerobically digested (Lundie and Peters, 2005). Sonesson et al. (2000), also highlighted AD has the option presenting the lowest environmental impacts of all solid waste management systems, while composting offered environmental advantages compared with incineration methods. Additionally, Björklund et al. (1999) concluded that large-scale centralized composting might increase environmental impacts relative to AD.

Therefore, AD and AC mixed systems seem to be the most sustainable option from an environmental point of view. This fact, also highlighted this option as the best one to comply with the principles of circular economy, and with the Sustainable Development Goals (SDG), specially with the SDG6: to ensure availability and sustainable management of water and sanitation for all. In this general context, it is suggested the need of promoting strategies conducive to the source-separated and selective collection of FLW. Finally, the comparative between BAU and 2DS presents important differences with the previous work, as previously they were significant differences and, in this work, only for the water scarcity footprint in S4 in the region of AN, a difference was detected.

3.3.3 Conclusions

The results obtained highlighted, in terms of water scarcity, scenarios that include AD and, to a lesser extent AC, as those that present lowest environmental impacts. In contrast, scenarios with incineration presented the highest impacts. On the other hand, no significant variations between BAU and 2DS situation were found, with the exception of the water scarcity footprint in AN if S4 is considered. Regarding the water degradation, the evolution of the energy mix will influence the impact of AD and incineration technologies, being S3 (75% AD and 20% AC) the worst option in BAU, and the best option in 2DS, while S4 (90% incineration) was highlighted as the worst option in a 2DS framework.

However, many of the regions in the different scenarios of the WF profile do not improve or worsen the situation, being especially remarkable in the water scarcity of the S6, in which no region varies its results in regard to the currently situation, neither in BAU nor in 2DS frameworks. In general, the regions of the North of Spain and the islands have the lowest water scarcity and degradation, being less influenced by the type of FLW management and with the compliance of the PA targets.

Results aimed to help by the decision-making process in terms of future FLW management in Spain. In this line, they confirm and reinforce the need to develop regionalized FLW management policies in Spain, moving from national to regional approaches when developing future roadmaps. This fact should be transcribed in an increasingly regional decision-making capacity future policies, focusing firstly on regional criteria and characteristics of the FLW management systems, instead of national plans seeking uniformity of strategies.

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CHAPTER 4

Consequences of strong short-term fluctuations: the COVID-19 outbreak

4.1. Framework

The COVID-19 outbreak provided an opportunity to validate the models and methodologies developed in a normal situation in Chapter 2 of this Thesis. Thus, in Chapter 4 the COVID-19 outbreak was used as a field of experimentation to analyse the evolution of the FLW generation and management problem in Spain in an unprecedented situation of strong short-term fluctuations in the system. In this line, this chapter deepens the objectives approached in Chapter 2: The **Objective 2** aims to quantify the FLW of the Spanish FSC, introducing specific calculation methodologies for different categories of food and different stages of the FSC. The **Objective 3** introduces the development and calculation of indicators of sustainable behavior that allow to evaluate the nutritional, the environmental (different impact categories) and the economic goodness of the different stages of the FSC. The **Objective 4** addresses the assessment of different FLW management alternatives under a food circular economy approach. Finally, the **Objective 8** highlights the need to find a more sustainable way of eating, looking for healthier and more environmentally friendly diets, contributing to climate change mitigation. The paper included in Section 4.2 is listed as follows:

1. Aldaco R, Hoehn D, Laso J, Margallo M, Ruiz-Salmón I, Cristobal J, Kahhat R, Villanueva-Rey P, Bala A, Batlle-Bayer L, Fullana-i-Palmer P, Irabien A, Vázquez-Rowe I **(2020)** Food waste management during the COVID-19 outbreak: a holistic climate, economic and nutritional approach, *Sci. Total Environ.*, 742, 140524.

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

4.2.1 Introduction

This section is located in the context of the Spanish lockdown in March, April and May of 2020. During that time, in general terms household food consumption increased significantly across all food categories. The main hypothesis of the research developed in this section is to consider that the 'strong short-term fluctuations and changes' of eating habits could have significant direct and/or indirect consequences in the 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.

4.2.2 Methods

The methodology developed in this study was established under a life cycle thinking approach since it involves all the stages of the FSC (ISO, 2006a). The methodology, which follows the LCA standards, is divided into four steps (ISO, 2006a, 2006b). The Spanish FSC 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-Monserrate 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 MFA was necessary (based on section 2.2), 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.

Goal definition

The goal and scope of this study was to assess the economic, nutritional and environmental (i.e., climate change) consequences along the Spanish FSC 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 FSC 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 FSC 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.

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 emissions 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, 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 functional unit 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^{-1} day^{-1}). The system boundaries comprise the entire supply chain of a food system, following the one considered in previous chapters of this Thesis 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 4.1, as well as FLW throughout the entire FSC (Vázquez-Rowe et al., 2019), acknowledging that, as mentioned before, depending on the stage of food production, either FL or FW are considered.

Spanish food supply chain and food loss and waste scenarios

The scenarios proposed in this study are summarized in Table 4.1 and described in detail below. 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.

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.

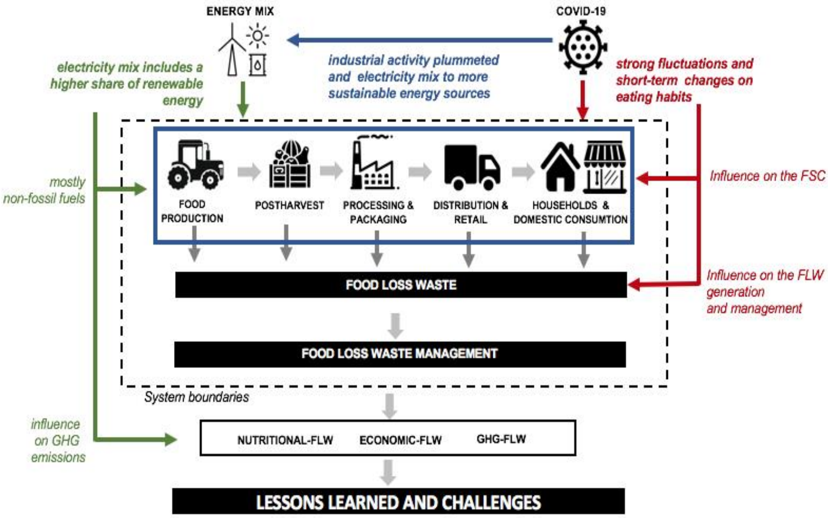

Figure 4.1 Overview of the functionality and system boundaries of the Spanish food system influenced by the COVID-19 pandemic.

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. 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 4.2 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 extradomestic consumption was hardly altered, since the state of emergency did not start until March 14 (Saturday), i.e., from Monday 11 to Friday 13, 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.

Table 4.1 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 Weeks 12–15, fuels 2020	86.1 (b) 100 (c)	13.9 (b) 0.0 (c)	Mostly non-fossil fuels

(a) Detailed information about the electricity mix is included in Table A3.1 of the Annexes.
(b) Extra-domestic consumption was available for most of week 11, excepting the
(c)Weeks 12–15.

Life cycle inventory

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, 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 recognizing, for instance, independent categories for fresh, frozen and processed fish but does not split fresh and frozen meats and vegetables.

Table 4.2 Food purchase rates during weeks 11-15 of COVID-19 and the same period of 2019 (kg/ cap^{-1} $week^{-1}$). 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

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 regions (i.e., 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 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 FLW was assumed (Sphera, 2019).

ii. Incineration with energy recovery. Incineration was based on the Sphera dataset for the biodegradable waste fraction in 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 495MJ of electricity and 1,277MJ 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 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 NOX reduction, two thirds using Selective Non-Catalytic Reduction (SNCR) and one-third of SCR was used. Regarding solid residues, the incineration of one metric ton of waste produces 220 kg of BA and 42 kg of boiler ash, filter cake and slurries. Once metal recovery and ageing are 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 below.

Nutritional data were obtained from the food composition tables of the Spanish Institute for Education in Nutrition and Dietetics (Farran et al., 2004). Table A3.2 of the Annexes 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 A3.3 in the Annexes). 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).

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 Section 2.2 (Chapter 2).

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.

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 AD) 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 A3.1 of the Annexes. The pandemic has influenced the energy sources of the Spanish mix. The use of hydropower and solar energy has 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).

Life cycle impact assessment

Nutritional food loss and 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 nine nutrients (protein, fiber, minerals calcium, iron, magnesium and potassium, and vitamins A, C and E) that should be encouraged and three nutrients (saturated fat, added sugar and sodium) that should be limited, was used as shown in Equation 4.1.

$$\text{NRF9.3}=\sum_i w_i\left(\sum_{l=9}\frac{NR_l}{DV_l}\cdot 100-\sum_{m=3}\frac{LIM_m}{MRV_m}\cdot 100\right) \qquad [4.1]$$

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 (to limit), and *MRV* is the maximum daily recommended value for the nutrient *m*. *Wi* 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 et al., 2009). Hence, when a certain nutrient intake was higher than its RV, the intake of this nutrient was set to its RV.

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 4.2, from Vázquez-Rowe et al. (2019).

$$\text{E-FLW}_i=\sum_j \text{FLW}_{i,j}\cdot V_{i,j} \qquad [4.2]$$

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

GHG emissions (GHG-FLW). FLW contributes to the generation of GHG emissions in two ways. On the one hand, GHG emissions emitted along the FSC, 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 favour 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 4.3.

$$GHG\text{-}FLW_i = \sum_j FLW_{i,j} \cdot GHG_{i,j} \quad [4.3]$$

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

4.2.3 Results and discussion

Overall food loss and waste assessment

Figure 4.2 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 4.2a). 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).

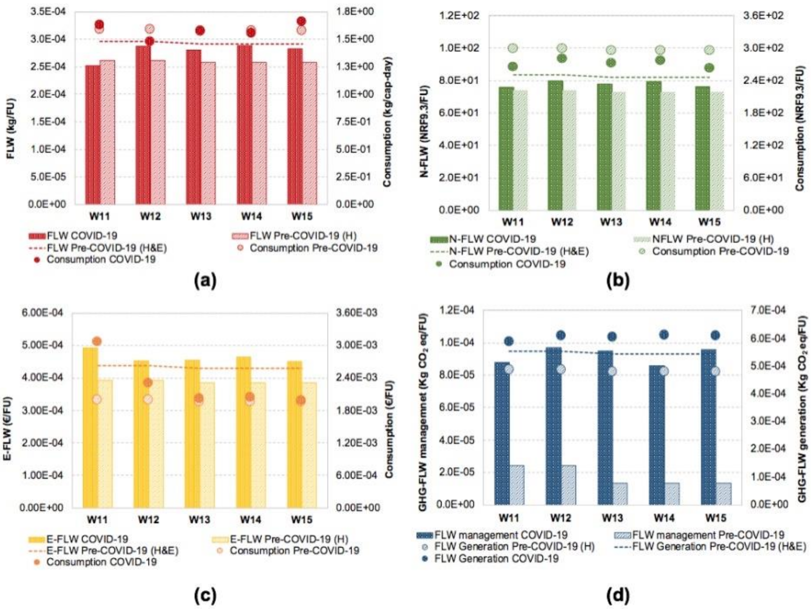

Figure 4.2 Overall FLW during pre-COVID-19 (P1) and COVID-19 scenarios (P2). (a) Total amount of FLW and food consumption; (b) FLW nutritional assessment; (c) FLW economic assessment; (d) GHG emissions assessment.

The nutritional content of food consumption during the outbreak decreased between 6% and 8% (see Figure 4.2b). The increase in consumption of alcoholic beverages, sweetmeats, snacks and processed foods constitutes the largest contributor to poor nutritional waste. The nutritional content per functional unit 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.

As shown in Figure 4.2c, when comparing the FLW costs, the previously described pattern is reversed. The FLW cost per functional unit 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 functional unit 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 4.2d). 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_{2eq} cap^{-1} $week^{-1}$).

Assessment of food categories

The assessment of food categories shows that fruits and vegetables are the categories most affected by the inefficiencies in the FSC. 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 4.3a, 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.

From an economic perspective, Figure 4.3c 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^{-1} $week^{-1}$) of total FLW, as compared to 47.3% in the pre-COVID-19 scenario (€ 2.85 cap^{-1} $week^{-1}$). 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.

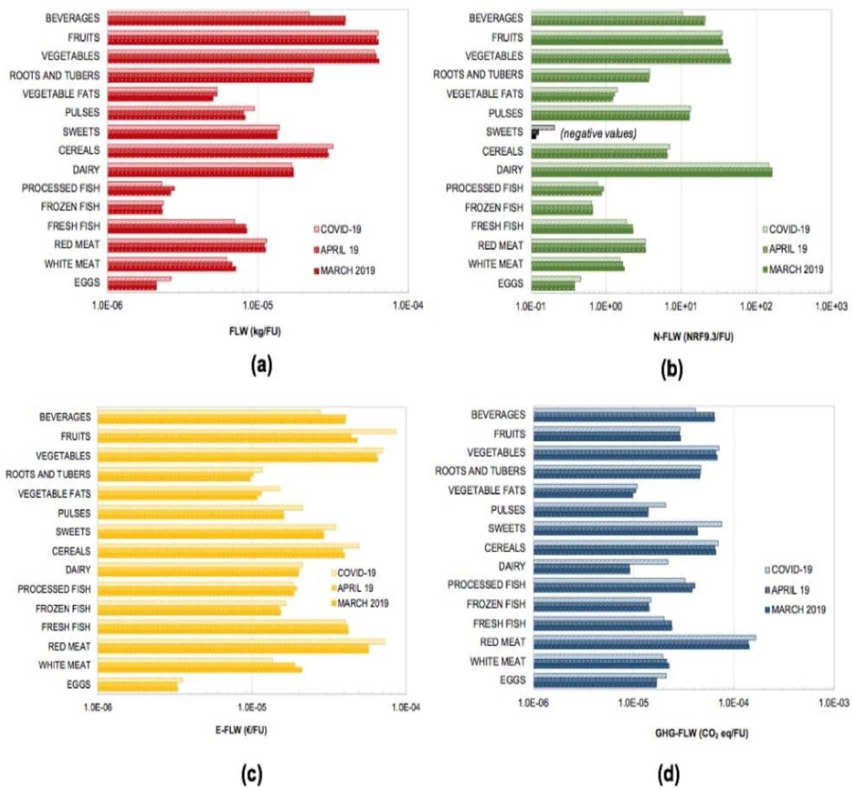

Figure 4.3 Assessment of food categories during pre-COVID-19 (P1) and COVID-19 (P2a) scenarios. (a) Total amount of FLW and food consumption; (b) FLW nutritional assessment; (c) FLW economic assessment; (d) GHG emissions assessment.

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.

Holistic assessment

Under a holistic approach, it is observed that the closer to the consumption FLW is produced, the costlier it becomes (see Figure 4.4a) 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 4.4c), 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.

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 suggested.

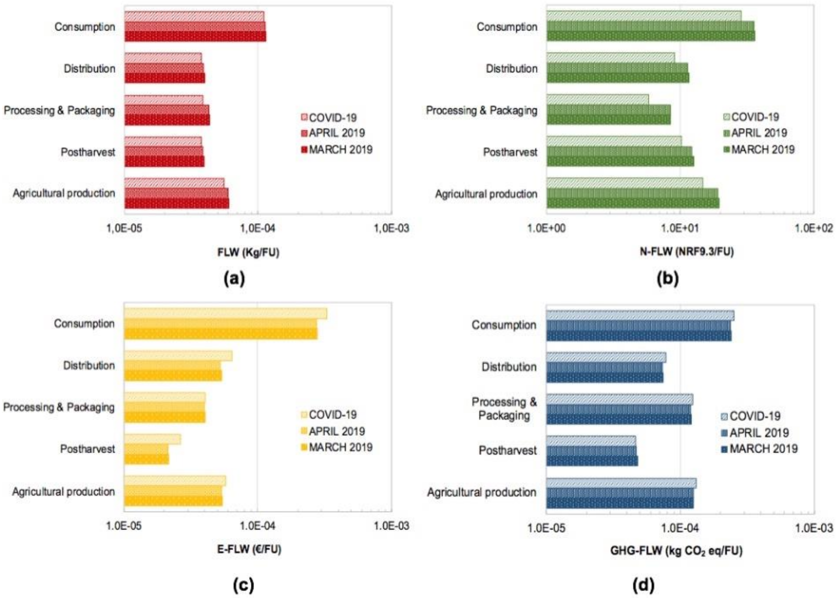

Figure 4.4 Holistic FLW assessment during pre-COVID-19 (P1) and COVID-19 (P2) scenarios. (a) Total amount of FLW and food consumption; (b) FLW nutritional assessment; (c) FLW economic assessment; (d) GHG emissions assessment.

The generation of FLW was estimated from a qualitative point of view, based on the existing knowledge available (see Table 4.3). 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.

Table 4.3 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%

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.

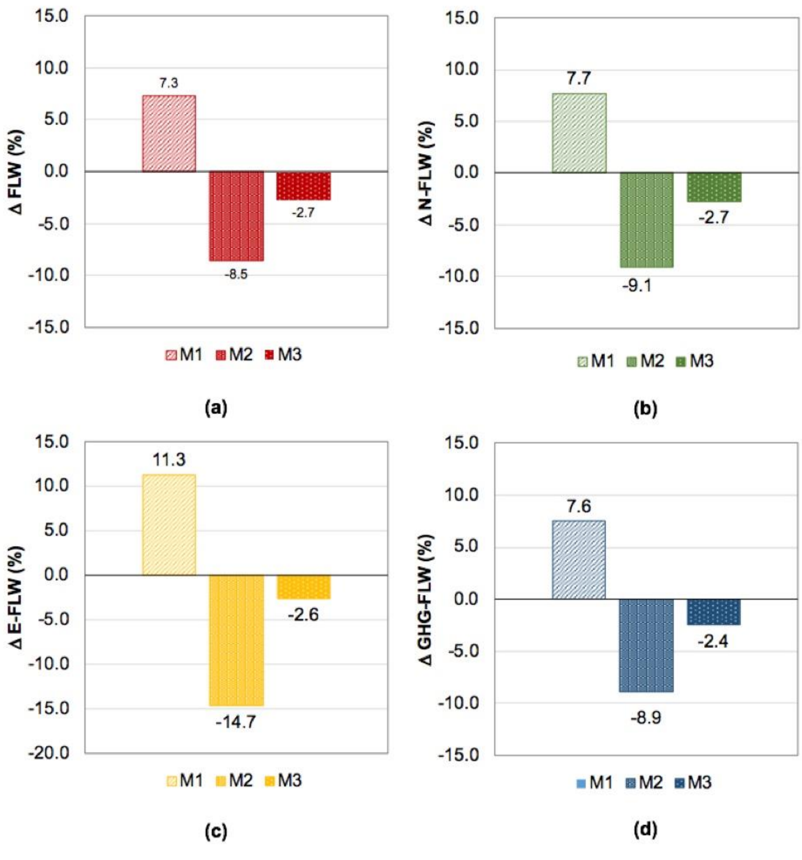

Figure 4.5 Sensitivity analysis for the considered scenarios during the COVID-19 outbreak: (M1) increase of 20% in the generation of FLW in households; (M2) reduction of 20% in the generation of FLW in households; (M3) losses in distribution and sales decrease by 20%.

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. Equation 4.4 was used to calculate the changes in overall FLW generation of the systems due to each parameter:

$$\Delta IA = 100\,\frac{IA_M - IA_B}{IA_B} \qquad [4.4]$$

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 4.4, 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%).

4.2.4 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 FSC. In fact, as defended by Hobbs (2020), the pandemic has offset a series of demand- and supply-side shocks that have disrupted FSC 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 FW 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 labelling. 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., 2020; 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 FSC, 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). However, 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 FSC, 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 FSC 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., "neighbourhood 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 FSC 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, 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 SDG2 and SDG12, but also with other international strategies, such as GHG emissions mitigation in the frame of the Paris Agreements 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).

4.2.5 Conclusions

Reducing FLW is critical to achieve certain SDG, especially SDG2 (Zero Hunger) and SDG12 (Ensuring sustainable consumption and production patterns). The COVID-19 outbreak has caused significant shocks inmost FSC. From an overall perspective, the crisis has shown that during the lockdown the amount of FLW generated in households has increased by 12% (as represented in Figure 4.6). 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 analysing the influence on the economic, nutritional and environmental cost along the FSC of the different FLW management options available, as well as possible FLW prevention measures (intended as diversion from landfill) and alternative valorisation routes (such as biorefineries) in the context of unexpected food demand patterns. From a European perspective, we hypothesize that the results obtained are highly extrapolated to other regional contexts, although it would be interesting to analyse 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 FSC 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?

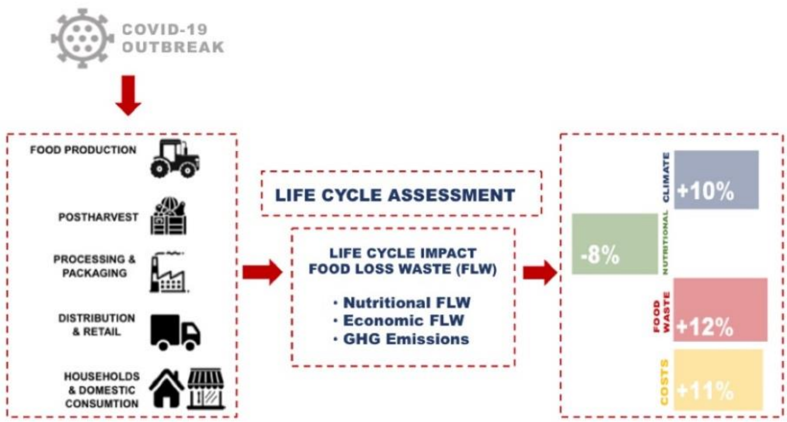

Figure 4.6 Graphical overview of the main results of this work.

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CHAPTER 5

Degrowth movement and the Sustainable Development Goals

5.1. Framework

Throughout the previous chapters, the context and problems surrounding FLW have been contextualized (Chapter 1), and the situation and different management options for FLW in Spain were analyzed, firstly from a national perspective (Chapter 2), and secondly, from a regionalized approach (Chapter 3). After it, the methodologies developed in Chapter 2 have been implemented in a real situation, were the COVID-19 outbreak derived in strong short-term fluctuations of the Spanish FSC. In this chapter, once the situation in Spain has been widely analyzed, its comparison with two international references is put into focus. All it, seeking to develop tools that lead to compare the Spanish situation with different international targets, in the first instance, and through it, with the situation of other countries and regions of the world. Therefore, two works have been developed. On the one hand, in Section 5.2, the sustainable degrowth needed to achieve sustainability in the Spanish food production and FLW management sectors, is analyzed through a novel methodology. On the other hand, the so-called SDG-Food index is presented in order to assess the Spanish situation of the FLW generation and management, regarding the five different SDG linked to food system (described in Chapter 1). All it aiming to introduce practical methodologies for being useful to policy-makers when analyzing the situation in Spain. Thereby, it is aimed to contribute to the **Objective 6** by defining strategies in the biological cycle of food through the application of the principles of the circular economy towards sustainability. Moreover, in Section 5.3 the **Objective 7** of the Water-Climate-Food Nexus is approached, as the SDG-Food index is based on those three pillars. The **Objective 8** is also included in this chapter (as well as in the Chapter 2). It highlights the need to find a more sustainable way of eating, looking for healthier and more respectful diets with the environment, that specifically contribute to the mitigation of climate change.

The papers included in Sections 5.2 and 5.3 are listed as follows:

1. Hoehn D, Laso J, Margallo M, Ruiz-Salmón I, Quiñones A, Amo-Setién FJ, Vázquez-Rowe I, Bala A, Batlle-Bayer L, Fullana-i-Palmer P, Aldaco R **(2021)** Introducing a degrowth approach to the circular economy policies of food production and food loss and waste management: towards a circular bioeconomy. *Sustainability,* 12. 13(6), 3379.

2. Hoehn D, Margallo M, Laso J, Ruiz-Salmón I, Batlle-Bayer L, Bala A, Fullana-i-Palmer P, Aldaco R **(2021)** A novel composite index for the development of decentralized food production, food loss, and waste management policies: a Water-Climate-Food Nexus Approach. *Sustainability*, 13(5), 2839.

5.2. Introducing a degrowth approach to the circular economy policies of food production and food loss and waste management: towards a circular bioeconomy

5.2.1 Introduction

Along the whole Thesis, the concept of sustainability has been under the focus. In this line, this section highlights the fact, that the sustainable development promoted over more than three decades ago with the Brundtland Report (1987) is a highly multi-disciplinary field of research that has been extensively studied during the last decades (Urbaniec and Duic, 2017). However, it is being questioned by several critical voices, due to an apparently ineffectiveness of the policies and strategies based on it for articulate responses to halt environmental problems (Infante-Amate and González de Molina, 2013).

Thereby, according to Georgescu-Roegen (1993) and Krausmann et al. (2009), the currently sustainable development strategies seem to be contradictory, as they avoid questioning the unremitting increase in the use of resources and the environmental impacts generation, although practice often suggests that it is not possible to reconcile an endless economic and productivity growth with environmental sustainability. Moreover, the International Panel for Sustainable Resource Management, highlights the fact, that the Global-North lifestyle is damaging not only its own environment, but also that of poorer countries and, in general, the planet as a whole (IPSRM-UNEP, 2010) as a big part of the environmental degradation in the Global-South is due to externalized environmental costs derived from the consumption life styles in the Global-North, which are not accounted for. This fact is often being hidden with fallacies with a colonialist slant by the Global-North such as the claim of the origin of environmental problems being in the presence of totalitarian governments, centrally controlled economies or lack of freedom, considering that the solution lies in the mantra of a need to bet on the free market with independence of the states, when this independence has never really existed (Mazzucato, 2011).

In this line, the Circular Economy Package of the EC puts an emphasis on closing the loop on the material use along the whole life cycle in order to achieve sustainability (Ragossnig and Schneider, 2019). Nevertheless, although it promotes strategies of zero-waste and circular economy, it does not set any sustainability limit in environmental impacts and resources use. This fact suggests that despite promoting policies searching for environmental sustainability, they may carry out the so-called greenwashing: the act of misleading citizens regarding the environmental benefits of a product or service (Delmas and Cuerel-Burbano, 2011). As a response of all these critical voices, the concept of sustainable degrowth is emerging internationally aiming to introduce in our societies social values, and new policies, capable of satisfying human requirements whilst reducing the environmental impacts and consumption of resources (Martínez-Alier et al., 2010).

In this overall framework, circular economy strategies for food production and FLW management systems are following the SDG agenda of halving by 2030 the per capita global FW generation at the retail and consumer levels, and the reduction of FL along production and supply chains, including post-harvest losses (FAO, 2019). Nevertheless, they are being developed based on a search for circularity, but without setting limits to the increasing amount of resources introduced into FSC, and the environmental impacts that it implies. Moreover, the SDG agenda puts the weight of waste halving at the end of the chain, but leaving the vague "reduction" goal in the early stages. All it, in a framework where at least one-third of all edible food production is wasted worldwide throughout the entire FSC (20% in the EU) (Gustavsson et al., 2011). The quantities of FLW could be much higher, especially in the early stages of the production chain (agricultural production, post-harvest and processing and packaging), as the loss or waste of animal and plant products which are non-edible or not originally intended to be eaten by humans, is not considered as FLW, even if this may have implications for food security and nutrition, or environmental impacts (FAO, 2019).

This work presents a methodology to determine the degrowth needed in the food sector at any national, regional, or local level, aiming to achieve compliance levels with the Paris Agreement targets. Among them, the goal of limiting global warming to well below 2°C above pre-industrial levels and pursuing efforts to limit it to 1.5°C stands out (UN, 2015). The methodology combines LCA with a degrowth approach, searching to highlight a spiral bioeconomy path, towards a circular bioeconomy, which is an emerging concept representing the renewable segment of the circular economy, necessary to build a carbon neutral future in line with the climate objectives of the Paris Agreement (EC, 2018a).

The concept of circular bioeconomy has been interpreted in this work as the level of degrowth calculated by the presented methodology, from which the circular production and consumption strategies should be implemented. It aims to be an easy-to-implement methodology for policy makers in the Global-North, in order to develop strategies looking to achieve real sustainability levels in which circular bioeconomy strategies can be implemented, as shown in Figure 5.1. It is based on the 4 R's strategy suggested by Latouche (2006) and Amate and González de Molina (2013): re-territorialization of production, re-vegetarianization of diet, re-localization of markets, and re-seasonalization of food consumption.

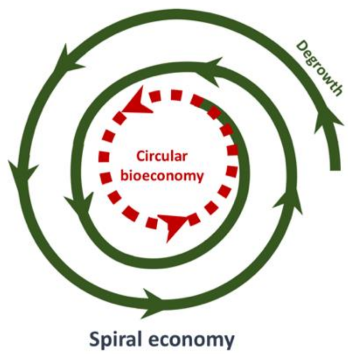

Figure 5.1. Degrowth transition needed through a spiral bioeconomy path, towards a circular bioeconomy (Resilience, 2018).

5.2.2 Material and methods

Goal and scope

The main goal of this work is to present a methodology to quantitatively assess the need of degrowth for implementing circular bioeconomy strategies, by reducing the emissions of GHG in compliance with the Paris Agreement targets. In order to implement the methodology, the case study of the Spanish FSC and FLW generation in 2015, as a country in the Global-North, was presented (as done along the whole Thesis). The methodology includes a first step of modelling the different scenarios in GaBi software (Sphera, 2020), following the LCA international standards ISO 14040 (2006) and ISO 14044 (2006). The developed model considers again that the FSC is divided in four stages: agricultural production, processing and packaging, distribution and consumption. According to a FAOSTAT definition (FAO, 2014), the model includes 11 different food categories: cereals, sweets, vegetable oils, vegetables, fruits, pulses, roots, dairy products, eggs, fish and seafood and meat. Regarding the definition of FLW, as described in the previous chapters, FL is often associated with the decrease of edible food mass available for human consumption in the earlier stages of the FSC (agricultural production and processing and packaging). FW is most often associated with the behavior of retailers, the food service sector and consumers (i.e. the stages of distribution and consumption) (ERC, 2014). In the present study, FLW refers again to FL and FW occurring at every stage of the FSC (FAO, 2011). The environmental performance of the presented scenarios was evaluated for the period 2020-2040, considering the compliance with the Paris Agreement targets every five years related to 2015. The simulations over time were based on the energy mix projections developed by the energy systems model TIAM-UCL (Anandarajah et al., 2011). It considers 16 regions covering the countries of the whole world. For this study, data for the Western European Region, that includes Spain, were used. A methodological framework of the work is represented in Figure 5.2.

The main function of the system is the production of food and FLW generation, under four different simulated scenarios (explained below). In order to measure this function, a suitable functional unit has to be defined, to which all the inputs and outputs are referred. The functional unit should describe qualitatively and quantitatively the function(s) and duration of the analyzed product (EC, 2018). In this case, one ton of produced food and generated FLW in Spain in 2015 was assumed as the functional unit. In this work, the term “degrowth” is defined as the descent of any of the four pillars by increasing their respective targets (described below), and the term “reduction” is defined as the descent of GHG emissions produced through a degrowth of any of the four pillars.

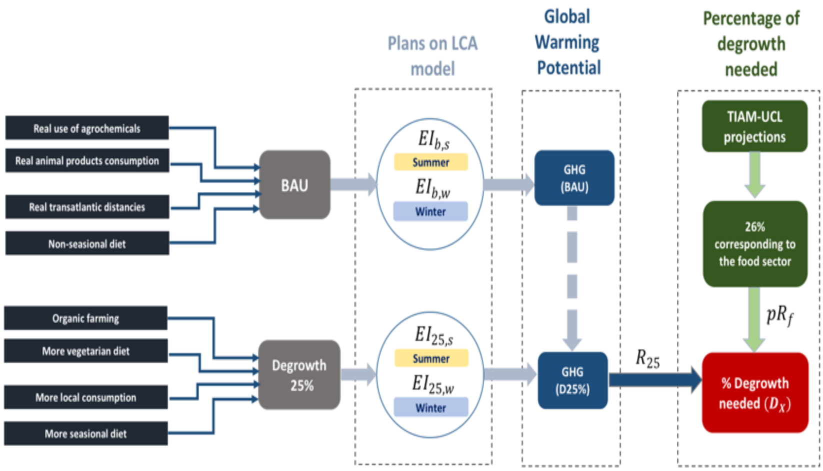

Figure 5.2. Methodological framework of the work.

Scenario analysis

As shown in Table 5.1, in order to measure the degrowth needed, four scenarios are considered and modelled. They represent, on the one hand, the actual situation of food production and FLW generation (business as usual, BAU), and, on the other hand, a 25% degrowth framework regarding the four pillars (D25%). It is based on an approach suggested by the Joint Research Center (Castellani et al., 2017) where a scenario test is assessed, in which the options of 25% and 50% reduction regarding diet changes, are considered. The results of the methodology for a given reduction percentage are proportional to each different percentage. Thereby, it was decided to apply the 25% reduction to the scenarios studied (including summer and winter). Nevertheless, other percentages would have given the same results.

The 4 R´s strategy implemented in the scenarios, suggests that a shift towards organic farming and corresponding changes in consumption patterns can contribute to substantial reductions in environmental impacts and resource use in the food system and, thereby, to sustainable degrowth (Infante-Amate and González de Molina, 2013). As seen in Table 5.1, this strategy considers four pillars in order to achieve sustainability through a degrowth transition: i) re-territorialisation of production (P1), ii) re-vegetarianisation of diet (P2), iii) re-localization of markets (P3), and iv) re-seasonalisation of food consumption (P4). These four pillars are translated into four targets: to switch to organic farming, to change over to a more vegetarian diet, to produce and consume locally, and to promote the consume of seasonal products (as explained in Figure 5.3).

Table 5.1. Considered scenarios highlighting if any of the four pillars are implemented. P1: re-territorialisation, P2: re-vegetarianisation, P3: re-localization, P4: re-seasonalisation.

Scenario	P1	P2	P3	P4
Baseline summer (BAU-s)	NO	NO	NO	NO
Baseline winter (BAU-w)	NO	NO	NO	NO
25% degrowth summer (D25%-s)	YES	YES	YES	NO
25% degrowth winter (D25%-w)	YES	YES	YES	YES

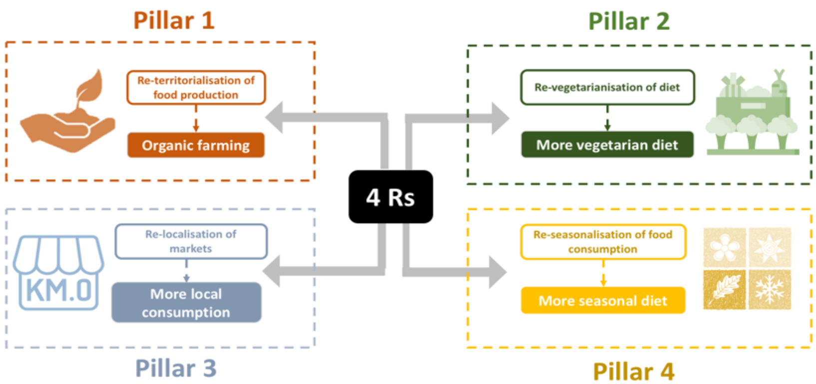

Figure 5.3. Diagram of the 4 R´s strategy based on Latouche (2006) and Amate and González de Molina (2013).

***i) Re-territorialisation of production**:* The P1 is assumed to be represented in an increase in the level of organic farming. This path is being highly promoted, as organic farming is a market set to continue growing and entails positive impacts on the environment and the biodiversity, as well as in creating new jobs, and attracting young farmers (Amigos de la Tierra, 2012). Although according to severally published scientific meta-analyses, organic farming yields range between 0.75 and 0.8 of conventional agriculture, there are positive effects of organic farming on soil fertility (i.e. almost total avoidance in the use of agrochemical products), biodiversity maintenance and protection of the natural resources of soil, water and air (Niggli, 2014). Moreover, yet all too often, it is precisely the emphasis on yield a measure of the performance of a single crop that blinds analysts to broader measures of sustainability and to the greater per unit area productivity and environmental services obtained in complex, integrated agroecological systems that feature many crop varieties together with animals and trees (Altieri, 1999). Additionally, there are many cases where even yields of single crops are higher in agroecological systems than in conventional crops (Lampkin, 1992). Finally, hunger is caused by poverty and inequality, not scarcity, and the world currently produces already enough food to feed 10 billion people, the world´s 2050 projected population peak (Holt-Giménez et al., 2012).

In order to measure this pillar, the D25% scenarios assessed the reduction in GHG emissions by a 25% degrowth in the use of agrochemicals (fertilizers, insecticides and herbicides) if organic farming increases. For it, a GaBi Software (Sphera, 2020) process was implemented in the LCA plans, which was assumed to be representative for the use of agrichemicals.

ii) Re-vegetarianisation of diet: The P2 is analyzed by comparing the GHG emissions of the currently diet and a diet based in a 25% reduction in the consumption of meat and fish and seafood, which are the animal products categories with the highest PED and EEL according to the data shown in Table 5.2. In the literature, within animal products consumption, meat is highlighted as the most relevant in terms of carbon and WF in high-income countries (Batlle-Bayer et al., 2020). This pillar will be translated in the target of increasing the 25% reduction of meat and fish and seafood in the rest of the categories. The 25% reduction in the quantities in each of the stages of the plans in GaBi Software (Sphera, 2020) was relocated in percentage terms as explained in the Life cycle inventory Section. The exception are the categories of vegetables and fruits, which stayed with the same quantities, without increasing, since of the remaining nine categories, they are the ones that clearly need a greater consumption of water resources and cold storage (Parajuli et al., 2019), impacts out of the scope of this work, but which have been taken into account for this decision. On the other hand, this second reduction target is in line with the recommendations of many works in the literature as well as with the new F2F strategy, as a more plant-based diet shows better environmental performance (EC, 2020), and will reduce risks of life-threatening diseases (Amigos de la Tierra, 2012).

***iii) Re-localization of markets**:* The P3 is correlated to a 25% reduction on transatlantic boat transport, related to the percentage of imported food in 2015, and considering an average transport distance of 4,000 kilometers (Amigos de la Tierra, 2012). To calculate this, the reduction of 25% of the import values obtained from Section 2.3 (Chapter 2), was implemented in the developed plans in GaBi Software (Sphera, 2020).

This reduction target, the so-called "food miles" reduction, is considered of high relevance in terms of degrowth as there are thousands of initiatives throughout the world claiming on the need of closing the circuits of production and consumption via development of local markets (Altieri, 2009). Moreover, transportation is one of the most challenging sectors to achieve sustainability due to its high dependence on fossil fuel products and increasing energy demands. According to a DEFRA report (Smith et al., 2005), reducing food miles will have a beneficial effect on sustainability, by reducing the environmental and social burdens of transport. It is not always clear whether a decrease in food transport would necessarily lead to an increase in sustainability, and there are even studies suggesting that "longer" supply channels generate lower environmental impacts per unit of production when measured in terms of food miles and carbon footprint (Malak-Rawlikowska et al., 2019). Nevertheless, in general it appears that an increase in food miles is correlated with negative sustainability impacts, by improving the environment through reduced pollution and increased biodiversity (Paxton, 2011). Exceptions are assumed either marginal, and were not include within the scope of this work.

***iv) Re-seasonalisation of food consumption**:* Finally, the P4 is assumed to be represented by a 25% substitution of vegetables and fruits by the remaining food categories in a winter plan for BAU and D25% in the modelling in GaBi Software (Sphera, 2020). Meat and fish and seafood stayed with the 25% degrowth target of P3. The remaining seven categories (i.e., eggs, dairy products, cereals, sweets, pulses, vegetable oils and roots) are assumed to be much more seasonal, or more easily to be preserved, then vegetables and fruits to be eaten during the Spanish winter. This reduction target has also been widely cited in the literature, and the advice on climate-smart food consumption given by many authorities and NGO worldwide, include the recommendation to eat seasonal foods (Röös and Karlsson, 2013). For measuring this target, the creation of an extra winter plan was required for the BAU and D25% scenarios, assuming summer as March to August (i.e. including the spring) and winter as September to February (i.e. including the autumn).

System boundaries

As presented in Figure 5.4, the developed LCA has a cradle to grave approach, including within the system boundaries the food and FLW generation in four stages of the FSC: agricultural production, processing and packaging, distribution, and consumption. The mass and energy balances from Sections 2.2 and 2.3 (Chapter 2) were used, in order to include the FLW and EEL of the considered food categories. Within the system boundaries, the PED of food transportation was included, but the collection and transportation of FLW were not considered, since it was assumed that it would not vary between the different scenarios.

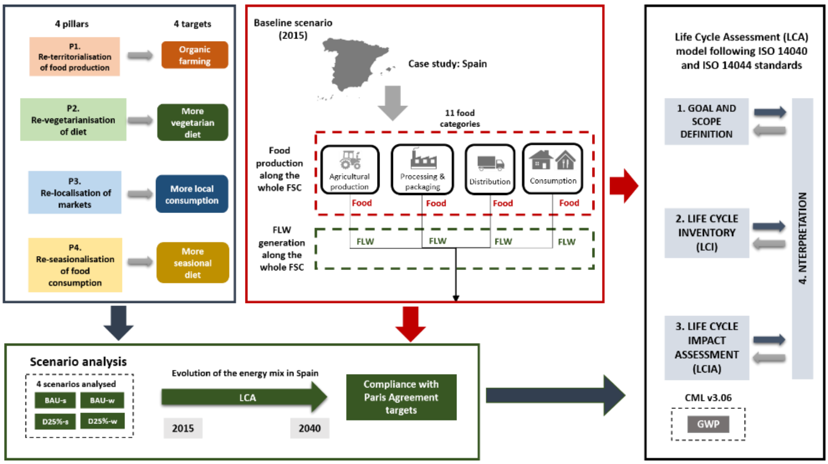

Figure 5.4. Conceptual diagram of the life cycle assessment methodology developed.

Life cycle inventory

The inventory was developed using the MFA of Section 2.2 (Chapter 2), making up an energy flow analysis, which was based on Section 2.3 (Chapter 2). The data on PED for food production and the EEL by FLW generation, are represented in Table 5.2.

The allocation, conversion and FLW factors used, were extracted from Gustavsson et al. (2013). The exception were concrete products, such as apples and bananas, for which specific FLW factors from Vinyes et al. (2017) and Roibás et al. (2016) were used. For the LCA modelling it was required the total energy embedded in the average Spanish diet for each food category. This information was obtained from Batlle-Bayer et al. (2019a), originally composed by 60 food categories, and grouped into the 11 categories considered in this work (as seen in Table 5.3).

To proceed to the methodological calculations explained previously, the percentages of all the categories with the exception of meat, fish and seafood, vegetables and fruits, were calculated. Those percentages were used to calculate the amount of food in mass that is redistributed in the rest of the categories (and its associated energies) with respect to P2 or P4. The P4 only takes place in the D25%-w, and due to it, the redistribution in D25%-w includes the 25% of the amount from the four mentioned categories, and the redistribution in D25%-s includes only the 25% of the amount from meat and fish and seafood, keeping the quantities of vegetables and fruits stable. As done in other previous sections, in order to determine the degrowth need from 2020 until 2040, the electricity mix simulations according to the TIAM-UCL energy systems model for a path of reducing the GHG emissions in compliance with the Paris Agreement targets, were used, based on the projections presented in Section 3.2 (Chapter 3). The evolution in a compliance framework, as explained in Chapters 3, suggested an enormous increase of nuclear energy until 2040, highlighting, thereby, that certain decarbonization policies in the electricity sector may foster the rise of a controversial energy source (i.e., nuclear), which opens the debate on whether the final outcome justifies any strategy to meet the Paris Agreement targets. Moreover, the projections suggested a reduction of the energy generated by biomass in 2025, which nearly disappearing by 2040.

Table 5.2. Total primary energy demand and embodied energy loss of food produced and food loss and waste generated in Spain in 2015 (in petajoules per total of tons), based on Section 2.3 (Chapter 2).

Stage		Eggs	Meat	Fish and seafood	Dairy products	Cereals	Sweets	Pulses	Vegetable oils	Vegetables	Fruits	Roots
Agricultural production	PED	29.0	149.8	86.9	38.7	74.5	4.3	13.4	19.7	90.4	18.9	9.1
	EEL	1.5	7.9	4.6	2.0	3.9	0.2	0.7	1.0	4.7	1.0	0.5
Processing and packaging	PED	18.7	96.7	56.1	25.0	48.1	2.8	8.7	12.7	58.3	12.2	5.8
	EEL	0.2	10.6	5.8	0.1	4.8	0.1	0.7	1.1	1.9	0.4	1.6
Distribution	PED	33.4	172.4	100.0	44.5	85.7	4.9	15.5	22.6	104.0	21.8	10.4
	EEL	1.3	13.4	12.9	0.4	3.3	0.2	0.5	0.4	2.4	0.5	0.4
Consumption	PED	12.8	66.0	38.3	17.1	32.8	1.9	5.9	8.7	39.8	8.3	4.0
	EEL	5.8	41.3	21.8	6.8	46.6	2.0	5.6	2.0	37.4	7.8	2.7

Table 5.3. Energy embedded (kcal) for each food category and percentages for the calculations of Pilar 2 and Pilar 4 (described in Figure 5.2), based on Batlle-Bayer et al. (2019a).

Food category	Energy embedded	(%)
Eggs	1059.1	15.4
Meat	5464.8	-
Fish and seafood	3169.5	-
Dairy products	1410.8	20.5
Cereals	2717.3	33.2
Sweets	155.6	2.8
Pulses	490.4	8.2
Vegetable oils	716.7	11.6
Vegetables	3297.0	-
Fruits	690.2	-
Roots	330.1	5.3
TOTAL	19501.4	

Life cycle impact assessment

For quantifying the potential GHG emissions of the scenarios simulated, the GWP, excluding biogenic carbon, was selected from the CML v3.06 methodology (Guinée et al., 2002). This choice was made considering that the assessment method has enough scientific endorsement and is widely used in the LCA literature (Guinée, 2015), and is in the list of recommended models at midpoint of the Product Environmental Footprint Category Rules Guidance (EC, 2018). The selection of the GWP indicator was done considering climate change as one of the most relevant impacts linked to food production and organic waste generation. It is acknowledged that other assessment methods or impact categories could have been chosen, but in this work, it was prioritized the use of one indicator of one single method for the degrowth assessment. The conversion factors used, extracted from GaBi Software (Sphera, 2020) were 0.0256 kilograms of CO_2 equivalents per megajoule of PED (in the case of food production) or EEL (in the case of FLW), and 72,700 kilograms of CO_2 equivalents per ton of ammonium sulphate used (assumed as equivalent to agrochemicals in agricultural production).

Assessment of food production and food loss and waste generation scenarios

For determining the reduction of the environmental impacts, total results for summer and winter were added and divided as presented in Equation 4.1:

$$R_{25} = \frac{(EI_{25,s}+EI_{25,w})}{(EI_{b,s}+EI_{b,w})} \quad [4.1]$$

where R_{25} is the reduction of the environmental impacts in D25%, $EI_{25,s}$ are the environmental impacts in D25% in summer (D25%-s), $EI_{25,w}$ are the environmental impacts in D25% in winter (D25%-w), $EI_{b,s}$ are the environmental impacts in BAU in summer (BAU-s), and $EI_{b,w}$ are the environmental impacts in BAU in winter (BAU-w). As the winter and summer plans correspond only to the half of the year, the results in the numerator and denominator of the equation, were multiplied by 0.5.

As a next step, due to the fact, that the total GHG emissions from 2015 to 2040 projected by TIAM-UCL are representing the whole production and consumption system in Spain, it was necessary to look for a reference indicator, in order to determine the percentage of GHG emissions in Spain corresponding only to the food sector. In this line, according to the EC (2016), industrial activities related to food systems require approximately 26% of the EU final energy consumption. As energy production is one of the sectors with higher environmental impacts, a 26% of the reduction needed of the GHG emissions in Spain, was assumed as representing the food sector.

This percentage was used to calculate for each year the projected reduction of GHG emissions related to the Spanish food sector in 2015.

The following part of the methodology is based on the combination of the two previously steps. When the assessment of the GHG emissions in the BAU for 2015 to 2040 is done, the percentage of total reduction in GHG emissions in all Spain can be calculated as follows:

$$tR_x = 100 - \frac{(GHG_x \cdot 100)}{GHG_0} \quad [4.2]$$

where tR_x is the percentage of total reduction in GHG emissions in Spain from 2020 to 2040, related to 2015. GHG_0 represents the total GHG emissions in the reference year, i.e. 2015, and GHG_x means the total GHG emissions in the compared year. In parallel, the percentages of the reduction of GHG emissions related to 2015, only for the Spanish food sector, are determined as stated in Equation 4.3:

$$pR_f = \frac{(GHG_0 - GHG_x) \cdot \alpha \cdot tR_x}{(GHG_0 - GHG_x)} \qquad [4.3]$$

Being pR_f the percentage of the reduction related to 2015 only for the food sector and α the reference for the part of the GHG emissions corresponding to the food sector, i.e. 26%. They have been calculated from 2020 until 2040. Finally, the degrowth needed in the four pillars from 2020 until 2040 was determined by implementing the comparison between BAU and D25% scenarios, and using Equation 4.4:

$$D_X = \frac{pR_f \cdot D_{25}}{R_{25}} \qquad [4.4]$$

Where D_{25} is the degrowth assumed in D25%, i.e. 25%; and R_{25} is the percentage of reduction of the GHG emissions between BAU and D25% scenarios, as explained previously.

Main limitations and assumptions of the study

As described in other previously sections, this study deals with a field where there are important gaps in the clarity of the reported data, both in terms of the generated quantities of FLW, and in terms of the relative importance of different recovery or disposal options (Arcadis, 2010). Moreover, it is difficult to link FLW generation and management, as the whole process takes time and in the meantime a fraction of the weight might be lost (e.g., due to drying). Differences can occur also due to import and export of waste, as well as unaccounted fractions. Moreover, existing statistics generally refer to the generation of biodegradable municipal waste, not to the generation of bio-waste or FLW, as mentioned in Section 3.2 (Chapter 3). Biodegradable municipal waste also includes paper, cardboard and biodegradable textiles. Additionally, in the more advanced stages of the FSC, FLW is usually mixed with general waste, which complicates the determination of the percentage that corresponds to FLW exclusively. The amount of FLW also depends on factors such as the time of the year and the region. Thereby, the main limitations are the uncertainty in the data used.

Another important discussion point is the fact that this section has suggested the TIAM-UCL results as a reference, in combination with the assumption of a 26% of representatively of the food sector, as LCA is able to compare scenarios but it may not be enough for determine if a scenario is improved enough (Hausschild et al., 2018). Thus, an analysis of sensitivity using the same methodology but considering other different reference indexes would be an important point for further discussion and development of the presented methodology. Moreover, the evolution in a compliance framework, suggesting an increase of nuclear energy, reaching 55% of the total electricity mix in 2040, is surprising and contradictory to what is the actual information that in 2019 just over 4% of global primary energy came from nuclear power. The reason for this high value in the model is due the fact, that the model was updated in 2015, when several nuclear power plants were planned, e.g. UK was going to double its nuclear capacity from 9 to 18 GW installed (100% increase). Since the price of wind and solar energy has fallen dramatically in the last 3 years, finally the UK decided not to go ahead. It is assumed that the same happened in other countries.

Regarding the P3, there are many arguments for using food miles for measuring sustainability of food production (e.g. GHG emissions), but they are also been cited a couple of arguments against using only food miles as a unique measure of sustainability of local production of food. Among all them, stands out the fact, that if there is a growth in business for smaller producers and retailers, there could be an increase in energy consumption or congestion as smaller vehicles are used and economies of scale in production are lost (Smith et al., 2021). Due to all this, it is often suggested that only through combining spatially explicit LCA with analysis of social issues can the benefits of local food be assessed (Edward-Jones et al., 2008).

According to the Product Environmental Footprint Category Rules Guidance, at least three relevant impact categories shall be considered in a LCA, or covering at least 80% of the total impacts (EC, 2018). Thereby, future works should consider including more indicators to assess if results would differ considerably. Additionally, in this study, only the GHG emissions related to energy consumption and the production and used of fertilizers in agricultural processes are considered. On-farm emissions were not included as a source of emissions, either outputs of the productions systems such as products demand and nutrient values of the food. All it could be a considerable underestimation.

Finally, the method used and the data assumed when building the model, may have considerably conditioned the results. Furthermore, it is important to highlight that this paper represents an exercise, which is purely theoretical, with multiple assumptions, simulating scenarios to obtain results, being any scenario simulation a simplification of reality.

5.2.3 Results and discussion

Within this section, results from the whole methodology are represented, focusing, first, in the reduction of GHG emissions regarding the food categories and the reduction of the GHG emissions at the different stages of the FSC. Second, the degrowth needed in the Spanish food sector from 2020 until 2040 in order to achieve the Paris Agreement targets, is determined, assessing also the influence of each of the four pillars when thinking of strategies for degrowth towards a circular bioeconomy.

Percentage of greenhouse gas emissions reduction regarding the food categories and stages of the food supply chain

When carrying out the analysis of the reduction of GHG emissions between the BAU and D25% scenarios, due to the way the LCA model is built to shape the pillars (as explained previously), the categories representing a reduction in the GHG emissions (as seen in Table 5.4) are meat, fish and seafood (both above 26% of reduction), vegetables (11.6% reduction) and fruits (12.8% reduction). Derived from the construction of the model and the energies associated with the food categories, the remaining seven categories increased their percentage of GHG emissions, reaching the highest increases the categories of pulses (+68.3%) and vegetable oils (+16.6%). The lowest increase was shown by sweets (+0.4%) and dairy products (+0.8%).

If the four considered stages of the FSC are analyzed separately, the stage of processing and packaging showed the highest reduction in GHG emissions (14.1%), followed by distribution (10.4%), agricultural production (8.2%) and consumption (7.7%). All of these are partial values on the specific emissions at each stage. In this sense, while processing and packaging energy demand was much less compared to the stages of distribution and agricultural production, a higher reduction was obtained since the assumed reduction in transatlantic boat transportation (reducing the primary energy used in imports by 25%) was included in the processing and packaging stage. These results reflect the fact that the analysis includes food production in addition to FLW generation. In terms of PED, which is associated with highest GHG emissions. This results are in line of the ones achieved in Section 2.3 (Chapter 2). Nevertheless, if only the FLW and its EEL are considered, the stages with the highest potentially rates of GHG emissions related the EEL, would be potentially the stages of consumption and distribution.

Table 5.4. Percentage of reduction of GHG emissions achieved between BAU and D25% scenarios. Positive values mean a reduction and negative values mean an increase in the emissions.

	% Reduction
Eggs	-8.1
Meat	26.7
Fish and seafood	26.1
Dairy products	-0.8
Cereals	-1.2
Sweets	-0.4
Pulses	-68.3
Vegetable oils	-16.6
Vegetables	11.6
Fruits	12.8
Roots	-5.0

Percentage of degrowth needed in the Spanish food supply chain

As represented in Table 5.5, the TIAM-UCL projections reflected a reduction needed in the GHG emissions in Spain between 41.9% in 2020 and 93.2% in 2040 in order to achieve compliance with the Paris Agreement targets (including all the Spanish sectors). From those rates of total GHG emissions reduction needed in Spain, following the equations presented in previously, the food sector will need to reduce their emissions between a 10.9% in 2020 and a 24.2% in 2040.

Table 5.5. Reduction of greenhouse gas emissions in Spain according to TIAM-UCL projections, and the corresponding percentage of the Spanish food sector, assuming a 28% of all.

	2020	2025	2030	2035	2040
% Reduction from 2015 (Spain)	41.9	58.4	66.8	77.1	93.2
% Reduction from 2015 (only food sector)	10.9	15.2	17.4	20.1	24.2
Degrowth needed in the 4 pillars	**26.8**	**37.3**	**42.5**	**49.0**	**58.9**

On the other hand, after performing the analysis between the four scenarios, the reduction in D25% reached percentages of 10.2% and 10.6% from 2015 until 2040 (as seen in Figure 5.5). Thereby, using the Equation 5, the degrowth needed in the 4 pillars for achieving the levels of GHG emissions reduction, in order to accomplish the climate targets, was calculated, reaching values between 26.8% (in 2020) and 58.9% (in 2040).

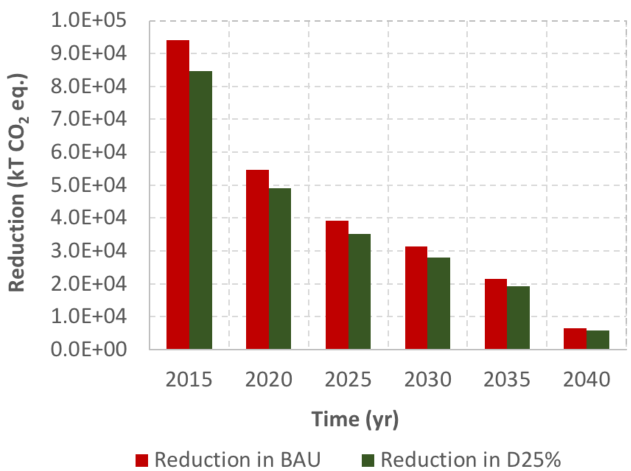

Figure 5.5. Representation of the GHG emissions in the baseline (BAU) and the 25% degrowth (D25%) scenarios from 2015 until 2040 (in kilograms of CO_2 equivalent).

If the four pillars are analyzed separately (as highlighted in Figure 5.6) in order to see the influence in the comparison between BAU and D25% scenarios, P2 represented the greatest influence, with a 78.5% from the total. That result, suggests the fact that reducing the consumption of meat and fish and seafood products seems to be clearly the strategy with the highest potential of influence when searching for degrowth through a spiral bioeconomy path until the achievement of the Paris Agreement targets. With much less influence, the second pillar in terms of its importance was P4 (14.9%), followed by P3 (6.3%) and P1 (0.3%). In this way, a more seasonal diet and more local consumption had a considerable influence as well, but the increase in organic farming would be a pillar with very low relevance in terms of degrowth in the Spanish food system towards the compliance with the Paris Agreement targets. As P2, P3 and P4 are strictly related, according to the results, a mixed scenario could be formulated to drive future food policies in Spain, promoting more plant-based food production and consumption, firstly, made up of seasonal plants as much as possible, and secondly, based on locally produced products. Organic production, in terms of degrowth needed, according to the results obtained, would occupy a secondary role. As a reference for developing national strategies, the F2F Strategy (Niggli, 2014) would be the most suitable, since it mentioned the three highlighted pillars.

In line with the results, highlighting the reduction of meat and fish and seafood consumption (P2), i.e. a more ovolactic diet, as the most useful path for the degrowth transition to a framework of real sustainability, there is a growing trend on publishing research assessing the environmental impacts of diets and dietary shifts (Batlle-Bayer et al., 2019b). More concretely, it is often highlighted the fact, that a new dietary culture which endorses plant-based foods is required, to contribute to better nutrition, food security and achievement of global sustainable development goals (Marinova and Bogueva, 2019). In the same framework, a general consensus is shown, regarding the fact that dietary changes can play an important role in reaching environmental goals, being the highest reduction potential mainly on lowering the amount and type of meat included in the diet, but also on the environmental performance of the food substituting meat (Hallström et al., 2015). This reduction would be also translated in health benefits, as in high-income western countries, large prospective studies and meta-analyses generally show that total mortality rates are modestly higher in participants who have high intakes of both red and processed meat than in those with low meat intakes (Godfray et al., 2018). Moreover, different works as the ones of Rosi et al. (2017) and Walker et al. (2018), stated that, to reach environmental sustainability as well as to increase the nutritional quality of diets, animal-based food products, as well as sweets, should be partially replaced with fruits, vegetables, legumes, and cereals. However, it is important to think not only in terms of dietary groups, but also of individual dietary habits, irrespective of dietary choice.

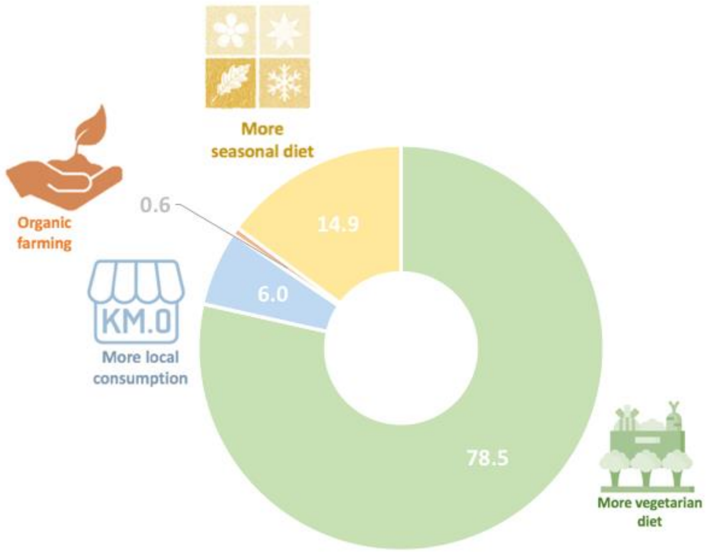

Figure 5.6. Representation of the influence of the four pillars in the degrowth needed in the Spanish food sector, showing the targets of P1 (organic farming), P2 (more vegetarian diet), P3 (more local consumption) and P4 (more seasonal diet).

It is important to remark that the results of this work could be influenced by the way of constructing the model, and the considered or not considered elements. Regarding the P3, the promotion of local food is a complex problem, where transportation is not the only factor that determines how efficient it is to consume local food. The dialogue over food miles has been largely centred not on its complex reality, but on a single variable, although local eating is about much more than distances of transport (Schnell, 2013). Other factors as recycling of nutrients, freshness/taste/nutritional content, technologies used for agricultural production, integration between producers and consumers (i.e. support local or rural economies and small-scale business), or knowing where food comes from, would be important to be considered in future works in order to adopt a more holistic overview of the impacts of local consumption (Benton et al., 2017). Additionally, local production does not always mean lower emissions of environmental impacts

(Coelho et al., 2018). Regarding the seasonality of food consumption (P4), it has been also highlighted in the literature as an important variable when defining the best choice of food consumption from an environmental point of view (Hospido et al., 2009). The results showing the lowest importance of P1 from the four pillars may indicate an argument in favor of those voices denoting that the production from organic systems is equal to or less than conventional yields due to the currently technological limitations (Seufert et al., 2012), being thereby, the ability to feed the world population through organic food production questioned. Nevertheless, the presented results of P1 could be also affected by the way of constructing the scenarios, and the fact of only considering the GWP as a reference. In this line, many authors have criticized that conventional agriculture, developed through the Green Revolution, generates high rates of pollution of the environment by the use of agrochemicals and fossil fuels, which produce many other problems besides hunger in the world. These other pollutants were not included in the analysis carried out in the present study. Additionally, they are studies suggesting that the world already produces enough food to feed nine to ten billion people, the population peak expected by 2050, and consequently the problem is not to produce more, but to better managed what is produced (Altieri, 2009). In this sense, increasing investment in organic production seems to be important for many other environmental and social aspects that have not been addressed in this work.

Finally, as highlighted previously, where TIAM-UCL projections showed a potential tendency of increase in the use of nuclear power, the search for a degrowth in the food production and FLW generation system in order to achieve a reduction of GHG emissions, should be combined with other complementary strategies together with climate policies. They exist previous experiences such as the ban of nuclear power developed in 1978 in Austria (BGBI, 1978).

5.2.4 Conclusions

The methodology presented in this section, implemented in the study case of the food production and FLW management in Spain, highlighted a needed of degrowth in the GHG emissions between 26.8% in 2020 and 58.9% in 2040. From the four pillars suggested, following the 4 R´s strategy, the reduction in the consumption of the categories of meat and fish and seafood

(P2) seems to be the most useful pat. It could achieve the 78.5% reduction of the total GHG emissions between the BAU and the D25% scenarios, much higher than the increase of seasonal products consumption in winter (P4), the reduction in transport distances (P3), and the reduction in the use of agrochemicals (P1). Moreover, results highlighted the stages of processing and packaging (14.1%) and distribution (10.4%) as the ones with more reduction potential in the GHG emissions if the pillars for degrowing are implemented.

If future strategies would focus on achieving this degrowth needed, once right-sizing has been achieved through the progress of degrowth, the aim should be to maintain a so-called steady state economy, with a relatively stable, mildly fluctuating level of environmental impacts and resources consumption at any context of the Global-North. In this line, a key research question to be answered is which countries should follow degrowth, which countries can still benefit from an economic growth, and which countries are closest to a steady state economy. It is clear that many countries in Western Europe and North America, the so-called Global-North, need to degrowth their resource use and environmental impacts before establishing a steady state economy. It is also clear that most of the countries in sub-Saharan Africa can still benefit substantially from economic growth, and that many countries in the Global-South should follow a path of decelerating growth. Nevertheless, this leaves a vast grey area in between where the appropriate development paths are unclear and future works on this field should try to clarify.

As in this section, the CML method has been assumed as representative for the analysis of the GWP, future works could use other methods and impact categories in order to assess the robustness of the methodology and the results presented in this work. In this sense, this section (and along this Thesis) has highlighted the controversial fact of an enormous increase in nuclear energy, which bears another danger, which is not really covered by available LCA indicators.

On the other hand, when developing strategies for improving the environmental performance of FSC and FLW management options, it is needed also to define the degrowth at least at regional level, as it may will change considerably between different regions. This would be another path of study for which different reference indicators would be needed, adapted to more local contexts.

Finally, this methodology aimed to be interesting for policy makers in order to be implemented at any other FSC at a national level if the TIAM-UCL projections are used, or at any regional or local level if other targets would be used. Future work should also include social aspects in order to expand this methodology, considering them as elements which should not be substituted for one another, i.e., more environmental sustainability cannot substitute social aspects, and viceversa.

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5.3. A novel composite index for the development of decentralized food production, food loss, and waste management policies: a Water-Climate-Food Nexus Approach

5.3.1 Introduction

As already presented in the previous chapters, nowadays, freshwater and food access are far from being ensured for a big part of the global population. Moreover, among these problems, food security is being affected by climate change. It is observed especially in African dryland areas and the high mountain regions of Asia and South America, due to declines in yields and crop suitability, as well as impacts in pastoral activities (Shukla et al., 2019). In this regard, as already mentioned, the energy consumption of food systems represents, globally, about 30% of the final energy use (FAO, 2011), and 70% of the world´s freshwater withdrawals are used for agriculture (as well as 78% of the eutrophication in oceans and freshwater reserves). Additionally, food systems produce around 26% of the anthropogenic GHG emissions (Ritchie and Roser, 2020). On the other hand, in a global context of increasing population, food production needs and global water use are expected to increase in 2050 by 60% and 50%, respectively (Vora et al., 2017).

Dietary choices are strong determinants of human health, but recent awareness has grown around the fact that foods and beverages we produce, choose, and consume, may significantly affect the environment (Rosi et al., 2017). According to Clark et al. (2018), Mediterranean, pescetarian, vegetarian, and vegan diets could reduce the incidence of diet-related diseases and improve environmental outcomes.

In this framework, as introduced in Chapter 1, in 2015 the United Nations member states adopted the 17 SDG, promoting a global political agenda in which environmental sustainability is one of the main pillars. To achieve it, a key point is undoubtedly the proper management of the waste generation. Within the broad spectrum of waste types, FLW can be highlighted due to the highly generation levels worldwide. To measure the level of compliance of any national, regional, or local context with the SDG, the development of composite indexes is being recommended for providing useful information to decision-makers (Guijarro and Poyatos, 2018). Different composite indexes are being established to monitor progress toward sustainable development, highlighting the SDG index, which originally was composed of 77 indicators but now compiles 99, for measuring the degree of sustainability in more than 150 countries (Diaz-Sarachaga et al., 2018). Based on the SDG index, Jabbari et al. (2019) presented a composite index called Development index (DEVI), which has a high correlation with the Human Development index. Moreover, different sectorial indicators already existed, as the SDG9 index, a measure of country progress towards achieving industry-related targets of the SDG9 (industry innovation and infrastructure) (Kynčlová et al., 2020). The Multilevel Sustainable Development index, considered all three domains of sustainable development (environment, society, and economy), including micro, meso, and macro agents. It was implemented for analysing 62 industries in the German economy (Lemke and Bastinit, 2020). Another example was the three dimensions Resource-Efficiency Capacity index suggested by Moreno and García-Márquez (2018). Furthermore, there are also indicators with a territorial approach, using data that are collected and reported sub-nationally, as is the case of the indicator promoted by Alaimo and Maggino (2020) that analyses the first three SDG (no poverty, zero hunger, and good health and well-being) regarding the different Italian regions.

In this context, an emerging body of research promotes decision criteria for sustainable FLW management related to the characteristics of food (Redlingshöfer et al., 2020), linking different food security and food system dimensions spanning from local to global levels (Pérez-Escamilla, 2020). In this field, Agovino et al. (2018) introduced a revised version of the so-called food sustainability index by computing two indices for 25 countries worldwide using data envelopment analysis. Azzurra et al. (2019) developed three indices for measuring sustainable food consumption, summarizing a set of variables for i) assessing organic consumption intensity, ii) the degree of both food sustainability concerns, and iii) sustainability in consumers´ lifestyle. Finally, regarding environmental impacts of different diets, Rosi et al. (2017) presented the Italian Mediterranean index in order to evaluate the nutritional quality of each diet, concluding that regardless of the environmental benefits of plant-based diets, there is a need for thinking in terms of individual dietary habits.

On the other hand, as the environmental impacts of water use, climate change, and food consumption are closely related to each other, the use of indicators highlighting this kind of linkages is still needed (Saladini et al., 2018). A good example is the Wastewater Reuse Effectiveness index, which couples biophysical and institutional models of Water-Energy-Food interactions (Kurian et al., 2019). Moreover, Laso et al. (2018) developed an integrated Water-Energy-Food-Climate Nexus Index (WEFCNI). It was used to assess the management of residues from the anchovy canning industry in the region of Cantabria (Spain). Additionally, Leivas et al. (2020) presented an integrated index combining the LCA and linear programming under a Water-Energy-Climate Nexus approach implemented in the spirit drinks field as a case study.

This work presents a novel composite index—the Sustainable Development Goals (SDG)-Food index—which interrelates five SDG (SDG2, SDG6, SDG7, SDG12, SDG13) through three different environmental impacts indicators related to the Water-Climate-Food Nexus for the specific analysis of FLW generation at any FSC. It aims to develop a sectorial indicator regarding food systems and to determine which SDG are of higher importance when developing policy strategies to reduce the impact of FLW generation. This indicator aspires to be implemented at different territorial levels, analysing different stages of the FSC and several categories of food. In order to test the index, once again, the case study of the Spanish FSC was analyzed. The assessment was first developed in the current context (2015) and then in different situations over time between 2015 and 2040 in a framework of (i) compliance (2DS) and (ii) non-compliance with the Paris Agreement targets (BAU). Among the targets, the goal of limiting global warming to well below 2°C above pre-industrial levels and pursuing efforts to limit it to 1.5°C stands out (UN, 2015). Finally, the evolution of the index in four different diets was also assessed:

i) An omnivorous/Mediterranean (currently) diet could be considered a plant-oriented dietary approach (Rosi et al., 2017). The Mediterranean diet represents the crystallization of the centuries-old cooking legacies of different civilizations (Hidalgo-Mora et al., 2020), and is considered one of the healthiest dietary models (Zani et al., 2016). It is characterized as containing large amounts of fruits, vegetables, whole grains, legumes, moderate amounts of seafood, and small amounts of other meats. Moreover, olive oil is used as the primary oil (Clark et al., 2018).

ii) A pescetarian diet includes fish, dairy products, and eggs. In other words, it is a vegetarian diet including fish and seafood (Guinée et al., 2002).

iii) A vegetarian diet includes cereals, roots, sugar, vegetable oils, vegetables, fruits, pulses, dairy products, and eggs (Guinée et al., 2002).

iv) A vegan diet is a vegetarian diet excluding dairy products and eggs (Guinée et al., 2002).

5.3.2 Methods

Figure 5.7 depicts the presented methodology to determine a composite index to evaluate FLW generation based on water, climate, and nutritional impacts related to the five SDG: i) SDG2 to end hunger, to achieve food security and improved nutrition, and to promote sustainable agriculture; ii) SDG6 to ensure availability and sustainable management of water and sanitation for all; iii) SDG7 to ensure access to affordable, reliable, sustainable, and modern energy for all; iv) SDG12 to ensure sustainable consumption and production patterns; and v) SDG13 to take urgent action to combat climate change and its impacts. From the five goals considered, SDG7 and SDG13 were assumed to represent the climate pillar of the index. In order to quantify those goals, the FLW generated along the whole FSC was transcribed into the GWP, excluding biogenic carbon, selected from the CML v3.06 methodology (Guinée, 2017). The method was selected as a widely used method in the LCA literature, as used in the previous Chapters 3 and 4. For the nutritional FLW analysis, SDG2 and SDG12 were considered and determined using the methodology for calculating the nutritional FLW footprint from cradle to gate ($NFLWF_{ctog}$) and nutritional FLW footprint from gate to grave ($NFLWF_{gtog}$), presented in Section 2.2 of Chapter 2. Finally, SDG6 was assumed to embody the water impacts and was quantified considering the WF results of Batlle-Bayer et al. (2020). As already explained in Chapter 3, the WF is an indicator of freshwater use that looks not only at the direct water use of a consumer or producer but also at the indirect water use (Chapagain and James, 2013). According to Hoekstra et al. (2011), the water footprint of a product comprises three color-coded components: i) green water (water evaporated from soil moisture supplemented by rainfall), blue water (water withdrawn from ground or surface water sources), and grey water (the polluted volume of blue water returned after production). The data used in this work represents only blue water, i.e., the water use for producing the food that was lost or wasted. The selection was due to the fact that blue water assessment is the most used in the literature, being green and grey WF less frequent measurements to date. According to the OECD (2008), the first step to obtaining a composite index is to normalize the individual indicators, and thereupon dimensionless values are aggregated using weighting factors. Therefore, after calculating the three proposed indicators related to the SDG2, SDG6, SDG7, SDG12, and SDG13; an internal normalization was done, using as a reference the highest value in the different food categories.

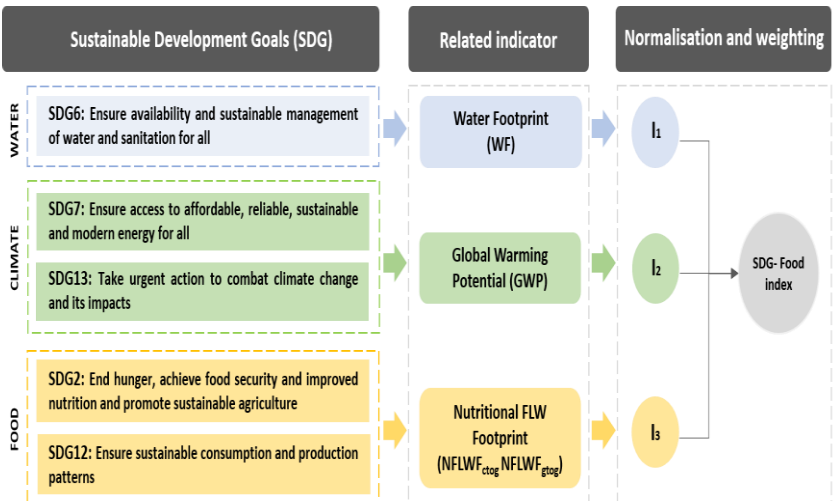

Figure 5.7. Conceptual diagram of the sustainable development goals (SDG)-Food index development methodology.

The three dimensionless values are aggregated in the global SDG-Food index, and therefore a weighting process is necessary. The weighting factor for the water and climate pillars was assumed to have a value of one, as they are represented by only one environmental impact category—the WF and the GWP, respectively. On the other hand, as the nutritional loss, representing the food pillar, was assessed by the $NFLWF_{ctog}$ and the $NFLWF_{gtog}$, which together are representing the whole FSC, a weighting factor of 0.5 was implemented.

The index has a minimum limit around six and a maximum around 33 (dimensionless). The interest of the presented methodology is i) the comparability between different stages of a FSC and food categories, and ii) the comparability of the calculated values of the index with future studies (e.g., countries, regions, cities, etc.).

5.3.3 Case study

System description

The methodology was applied to analyse the impacts of FLW generation in Spain along the FSC in 2015 (Figure 5.8). This case study, which is being the focus along the whole Thesis, was selected as Infante-Amate and González de Molina (2013) suggested that the present way the country feeds the Spanish population is an inefficient process. However, an assessment of other countries and regions, or a comparison between them, could be addressed in future works. The definition of FLW used in this work refers to FLW occurring at every stage of the FSC (FAO, 2014). The Spanish basket was again divided into 11 food categories: eggs, meat, fish and seafood, dairy products, cereals, sweets, pulses, vegetable oils, vegetables, fruits, and roots. Moreover, the four considered stages of the FSC included agricultural production, processing and packaging, distribution and consumption.

In addition, several hypotheses were introduced to determine the evolution of the impacts over time and under certain policy conditions. In the same line of the methodologies implemented in previous Sections, the environmental performance was assessed from 2015–2040 considering a framework of compliance (2DS) and non-compliance (BAU) with the Paris Agreement targets, based on the approach developed by Aldaco et al. (2019).

The simulations over time were constructed using the energy mix projections developed by the TIMES integrated assessment model from the University College of London (TIAM-UCL). These simulations consider 16 regions covering all the world (Anandarajah et al., 2011).

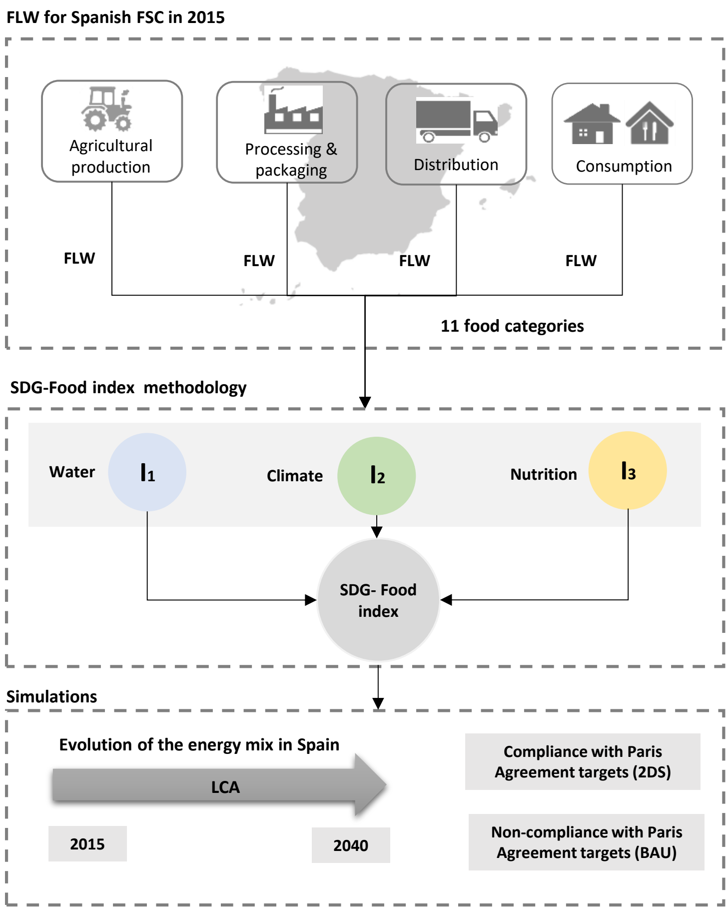

Figure 5.8. Description of the case study. FLW: food loss and waste; FSC: food supply chain; SDG: Sustainable Development Goals; LCA: life cycle assessment.

For this work, data for the Western European Region, which includes Spain, were used. As represented in Figure 5.9a, the projection in a BAU framework highlights a continuous increase in the energy produced from coal. Thereby, coal would be the source of around 60% of the total energy generation in 2040, followed by hydropower (20%), and natural gas, with less than 10%. On the other hand, in a 2DS framework, as represented in Figure 5.9b (and also explained in Chapter 3 and in Section 5.2) nuclear power seems to have an enormous increase, reaching a surprisingly percentage of 55% of the total electricity mix in 2040, followed by hydropower (20%) and onshore wind (10%). This indicates that certain decarbonization policies in the electricity sector may foster the rise of other problems (i.e., increase in nuclear energy generation). As previously remarked, this fact opens the discussion about whether the outcome justifies any strategy to meet the Paris Agreement targets. Finally, regarding biomass and biomass with carbon capture sequestration, both options suggested a start to decreasing by 2025 until almost disappearing by 2040.

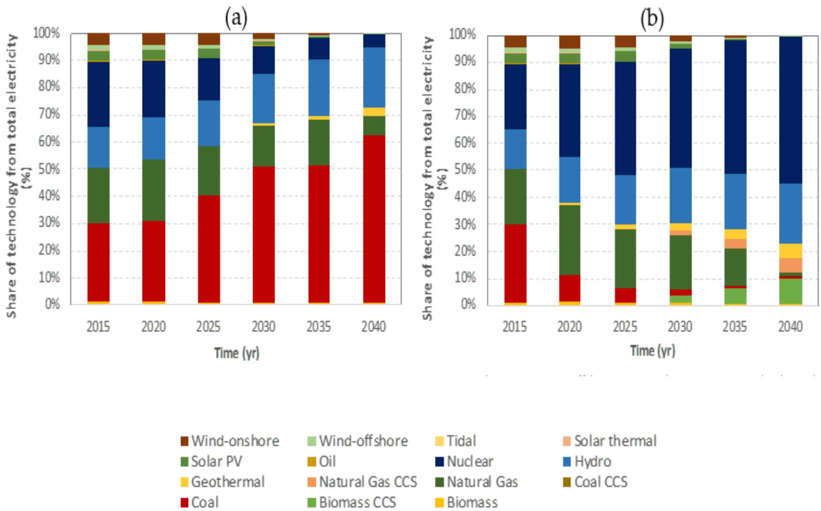

Figure 5.9. TIMES integrated assessment model from the University College of London (TIAM-UCL) energy mix simulations for the Western European region. (a) Projected BAU and (b) 2DS energy mix contexts from 2015 until 2040. PV: photovoltaic, CCS: carbon capture sequestration. Waste-to-energy technologies, such as thermal treatment, are included in the biomass.

Data collection and calculation

Firstly, the amount of FLW in the Spanish FSC and its EEL were determined using the MFA developed in Section 2.2 (Chapter 2) and the energy flow assessment presented in Section 2.3 (Chapter 2). Based on those inventories, the water, climate and nutritional indicators were calculated. To determine the climate indicator, the amount of primary energy required to produce each food category was converted into GWP using the database of the GaBi software (Sphera, 2020) and the CML v3.06 methodology (Guinée, 2014).

The allocation, conversion, and FLW factors used were extracted from Gustavsson et al. (2013). The exception were concrete products, such as apples and bananas, for which specific FLW factors from Vinyes et al. (2017) and Roibás et al. (2016) were used. For the quantitative calculations, data reported by the Spanish Department of Agriculture and Fishery, Food, and Environment (MAPAMA, 2015) were used. The water consumption assessment was based on Batlle-Bayer et al. (2020). The kilograms of water needed per ton of generated FLW for the 11 food categories (blue WF) are presented in Table 5.6. Finally, the data from the nutritional analysis carried out in Section 2.2 (Chapter 2) were implemented to construct the nutritional indicator of the index. The combination of these three data sets aims to provide a novel holistic Water-Climate-Food Nexus approach regarding the Spanish context of FLW generation for future policy-making, towards a life cycle Nexus thinking approach.

Table 5.6. Water footprint values assumed for each FLW category (in kilograms per ton), based on Batlle-Bayer et al. (2020). WF: water footprint.

Food category	WF (kg of water/ton FLW)
Eggs	458.9
Meat	665.1
Fish and seafood	413.0
Dairy products	435.3
Cereals	523.0
Sweets	234.2
Pulses	134.3
Vegetable oils	1517.0
Vegetables	214.1
Fruits	220.2
Roots	168.2
Total	4983.4

Main limitations and assumptions of the study

The data used of FLW generated have considerable limitations, as they are important gaps in the clarity of the currently developed databases (Arcadis, 2010). Additionally, the reported information normally refers to the generation of biodegradable municipal waste instead of specifying bio-waste or FLW generation, as mentioned in Section 3.2 (Chapter 3). In this line, biodegradable municipal waste can also include paper, cardboard, and biodegradable textiles. On the other hand, FLW is often mixed with general waste, especially in the more advanced stages of the FSC. Due to this fact, the determination of which percentage corresponds to FLW exclusively is a difficult task. The generation of FLW also varies depending on factors such as the time of year, and region. Thereby, the main limitations are the uncertainty in the data used.

Regarding the TIAM-UCL data used for the practical example, it is needed to highlight that any scenario simulation represents always a simplification of reality.

Moreover, this section described a methodology for developing a composite index, considering that indexes are an interesting and useful tool for guiding policy-makers. Nevertheless, there are several criticisms regarding the fact of analysing and quantifying complex problems through composite indexes, as it transforms complex realities into single quantitative or qualitative rankings. In that sense, Riege (2003) stated that aggregating different indicators into a unique number could be a source of losing a lot of information. Additionally, the OCDE (2008) suggested that composite indicators might send misleading policy messages if they are not well constructed or interpreted, leading to mistaken analytical or policy conclusions. In this framework, a recent publication of the FAO highlighted the SDG14 (marine resources) and SDG15 (terrestrial ecosystems, forestry, biodiversity) to be considered when searching for a higher environmental sustainability in food systems (Ringler et al., 2013), which are out of the scope of this work.

Finally, it is important to highlight that the weighting process carried out in this methodology is based on assumptions that inevitably respond in order to hide value judgments. In that sense, although many different weighting techniques exist, weights always represent value judgements with a certain level of uncertainty. Moreover, in order to test the replicability of the methodology presented in this work, it would have been interesting to implement it in multiple-case studies. It would be an important future path for assuring internal coherence of the findings and concepts presented in this work (FAO, 2019).

5.3.4 Results and Discussion

The aim of implementing a Water-Climate-Food Nexus thinking is to obtain results that interconnect with the three pillars, which are considered representative in order to measure the environmental impacts of any FSC and FLW management system. This approach is based on the hypothesis that results of any separate analysis can vary much from a holistic study approach including the three pillars. The results of this work aimed to be a first example to stand up future studies in other contexts. The first section analyses the results of the SDG-Food index in the current Spanish FSC, evaluating the different stages of the FSC and food categories. The second section analyses the evolution of the indicator in a BAU and 2DS frameworks in relation to the compliance and non-compliance with targets of the Paris Agreement. Finally, the third section highlights the index results regarding the four selected diets.

SDG-Food index in the Spanish food supply chain

The water, climate, and nutritional indicators denote that eggs, cereals, meat, and vegetables are the categories with the highest negative influence when aiming to achieve compliance with the five SDG analyzed (in red in Table 5.7). On the other hand, pulses, sweets, and dairy products showed the best environmental performance regarding the three indicators (in green in Table 5.7). The nutritional indicator (NFLWF) had the highest contribution to the SDG-Food index in 8 of the 11 categories because many of the NFLWF values were close to the maximum values, which were transcribed in higher normalized values compared to the other two indicators. The exceptions were the categories of eggs, where the WF was the one with the highest value; fish and seafood, where the GWP presented the highest impact value; and meat, where GWP and the NFLWF presented the highest values. According to the results, the NFLWF was, broadly, the one presenting higher impacts. Thereby, it is suggested that the Spanish policy-makers should put a special focus on the SDG2 (zero hunger) and SDG12 (ensuring sustainable consumption and production patterns), followed by SDG7, SDG13, and SDG6, all of which aim to achieve compliance with the SDG on the food sector (as explained in Chapter 1). This is in line with the conclusions of Section 4.2 (Chapter 4), who highlighting the reduction of FLW as a critical factor for achieving the SDG2 and the SDG12. On the other hand, the less vegetarian or more non-animal product-based diets, the greater influence the impacts have on WF (SDG6) and GWP (SDG7, SDG13), due to the values presented by the categories of eggs, fish and seafood, and meat.

Table 5.7. Total and individual values of the three pillars (normalized, i.e. dimensionless). GWP: Global Warming Potential, NFLWF: Nutritional Food Loss and Waste Footprint.

Food category	**WF (SDG6)**	**GWP (SDG7, SDG13)**	**NFLWF (SDG2, SDG12)**	
	I_1	I_2	I_3	I_T
Eggs	1.00	0.12	0.60	1.72
Meat	0.20	1.00	1.00	2.20
Fish and seafood	0.05	0.62	0.60	1.26
Dairy products	0.04	0.13	0.40	0.57
Cereals	0.72	0.80	0.87	2.39
Sweets	0.01	0.03	0.47	0.51
Pulses	0.01	0.10	0.40	0.51
Vegetable oils	0.02	0.06	0.73	0.82
Vegetables	0.13	0.64	1.00	1.77
Fruits	0.13	0.13	1.00	1.26
Roots	0.03	0.07	0.67	0.76
Total	2.36	3.70	7.73	13.79

Note: red means the highest negative influence, and green means the highest positive influence when aiming to achieve compliance with the five SDG analysed.

Although the database used in the previous chapters was used, the results differed considerably. Regarding the food categories with more impact, Section 2.2 (Chapter 2) suggested that fruit, vegetables, and meat have the highest rates of nutritional FLW in Spain, and Chen et al. (2020) highlighted cereals, fruits, and vegetables as the three major food groups contributing to nutrient loss, followed by meat, dairy products, and eggs. Moreover, Section 2.3 (Chapter 2) suggested meat FLW as the category with the highest EEL, which was much higher than fruit or vegetables. Recently, a new work developed by Laso et al. (2020) highlighted vegetables, fruits, and cereals as the categories less efficient in terms of generated FLW mass. In this work, if the total of the three indicators (WF, GWP, and NFLWF) of each FLW category is assessed, eggs, cereals, meat, and vegetables seem to be the categories highlighted as the most important when developing strategies for FLW management in Spain, by policy-makers, in order to achieve compliance with the five SDG assessed. This reinforces the importance of seeking holistic approaches when determining the best political decisions for the future. If the index values are analyzed in stages, the agricultural production and consumption showed the highest values (13.02 and 12.99, respectively). On the other hand, the stages of distribution (12.23), and processing and packaging (11.73) showed the lowest values, as seen in Table 5.8. Those results are in line with the previously mentioned works (when they include an assessment by stages), and the previous chapters of this Thesis, as they agree with the fact that strategies should focus on the beginning and end of the FSC, suggesting the possibility of decentralizing the FLW management strategies.

Table 5.8. SDG-Food index results, regarding each considered stage and the totality of the food supply chain (in 2015). Total means the index results of the totality of the food supply chain, instead of the sum of the individual results of each stage (i.e., results of singular stages cannot be added). Values are normalized, i.e., dimensionless.

Stages	WF (SDG6)	GWP (SDG7, SDG13)	NFLWF (SDG2, SDG12)	SDG-Food index
	I_1	I_2	I_3	I_T
Agricultural production	1.79	3.57	7.66	13.02
Processing and packaging	1.49	2.58	7.66	11.73
Distribution	1.77	2.66	7.80	12.23
Consumption	1.33	3.86	7.80	12.99
Total	2.36	3.70	7.73	13.79

Figure 5.10 represents the importance of each category by each of the indicators in the four stages of the FSC. As can be seen, the fact that agricultural production and consumption are the stages with the highest impacts is not determined by the NFLWF, which practically does not vary between stages, but is determined by the differences in the WF and GWP. In the agricultural production stage, the categories with the highest contribution to the index value are meat (2.17), eggs (1.79), and cereals (1.52). In the stage of processing and packaging, the highest values are those of cereals (2.18), meat (2.00), and fish and seafood (1.29). In the distribution stage, the categories of cereals (2.24), meat (2.00), and fish and seafood (1.56) stand out. Finally, in the consumption stage, the categories with the highest values are cereals (3.00), meat (1.98), and vegetables (1.83). Thereby, the four categories that were highlighted when analysing the total results (eggs, cereals, meat, and vegetables) presented also the highest influence at each stage. Additionally, the category of fish and seafood in the processing and packaging and distribution stages presented an important influence as well. It is interesting that the one with the highest values for three of the four

stages was the category of cereals. This fact connects with the conclusions of Section 2.3 (Chapter 2) in relation to the presented Energy return on investment - Circular economy index (*$EROI_{ce}$*), suggesting that FLW cereals in Spain have a high level of EEL, as well as a specific potential as a source for energy recovery, especially through AD.

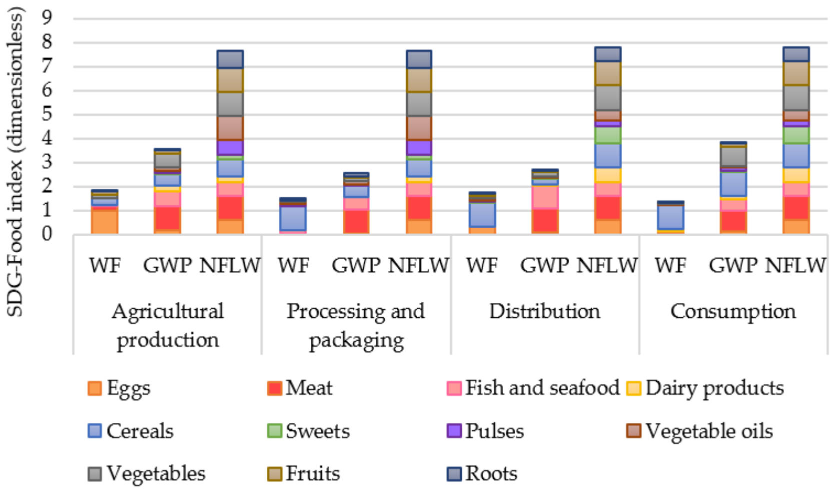

Figure 5.10. Each food category on each stage and pillar of the SDG-Food index (normalized, i.e., dimensionless).

Finally, regarding the SDG-Food index, a value of 13.79 was determined, which, in accordance with the minimum and maximum possible on the index scale, is in a medium-high range. If this value is compared with the current ones of the SDG index, Spain is in the 17th position with an index value of 78.11 out of 100 (Sachs et al., 2020), which proportionally would be an equivalent value to the medium-high value obtained in this work. Thus, although this study focuses on only five goals, the results seemed to be by the range of values of the SDG index.

This value could be compared with newly calculated indexes in other countries, regions, or localities by implementing the same methodology in other works.

SDG-Food index in a framework of non-compliance and compliance with the Paris agreement targets

If the scenarios of non-compliance and compliance with the Paris Agreement targets are applied to the data, with the foreseeable evolution of the energy mix, the SDG-Food index shows a decrease, i.e., higher sustainability and compliance with the SDG, in all stages and in the total value for the 2DS framework. Figure 5.11 represents the total values, whose trends are similar for the separate stages. Thus, in 2040, the index would decrease by 24.8% compared to 2015, reaching the value of 10.3. On the other hand, if the Paris Agreement targets are not achieved (BAU framework), there would be an increase in the index in all stages and in its total value, increasing 19.0% in 2040 compared to 2015, reaching a value of 16.3. If the specific values of each stage are observed, the highest values would be found in the consumption stage in 2040 with a value of 15.6 (in the BAU framework). On the contrary, the processing and packaging (9.3) and consumption (9.4) stages would reach the lowest values in 2040 (in the 2DS framework). However, the differences are not very significant in the evolution between each of the stages, and the interesting information is the reduction of the index that would be achieved by complying with the Paris Agreement targets until 2040, as well as the increase in the index that this would be happening in a situation of non-compliance with the targets. This results reinforce the statement presented in other works, showing how the Paris Agreement targets can be made consistent with food security objectives and how multiple SDG can be achieved (Doelman et al., 2019).

SDG-Food index regarding different diets

Food commodities have been assessed according to four different diets: omnivorous-Mediterranean (currently), pescetarian, vegetarian, and vegan diet. The current diet in Spain is assumed as a mix between omnivorous and Mediterranean diets. As seen in Figure 5.12, the results indicate that the lowest values of the index, i.e., better environmental performance, for the vegan diet, followed by vegetarian and pescetarian diets (in all stages of FSC). Specifically, a vegan diet would reach a 29.88% reduction in the values of the SDG-Food index with respect to the current diet, a vegetarian diet 18.33%, and a pescetarian diet 13.06%. The greatest differences between a vegan diet and the current diet occur in the stages of agricultural production and processing and packaging, where the differences are 37.50% and 37.14%, respectively. An exception is highlighted in the distribution stage, where the pescetarian diet appears with a slightly lower value of the index than the vegetarian one.

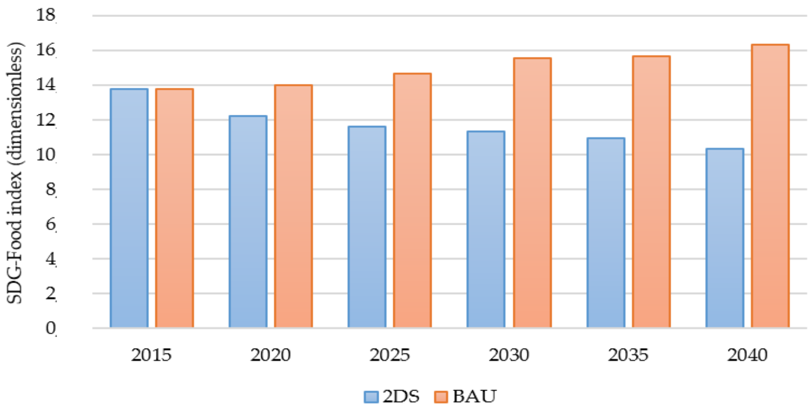

Figure 5.11. SDG-Food index results regarding the total of the food supply chain between 2015 and 2040, in a scenario of non-compliance (BAU) and compliance (2DS) with the Paris Agreement targets (normalized, i.e., dimensionless).

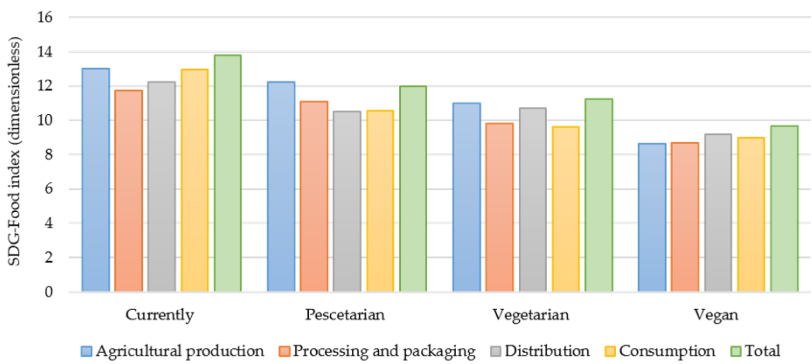

Figure 5.12. SDG-Food index results regarding the four different diets considered (normalized, i.e., dimensionless).

The results are in line with a ones in the previous section, regarding the degrowth assessment of the Spanish FSC, where a re-vegetarianisation of the diets seemed to be the best pillar for achieving a spiral bioeconomy towards sustainable food production and FLW management systems. Moreover, in the literature, there are also a wide range of works concluding that “going back” to plant-based diets worldwide seems to be a reasonable alternative for a sustainable future (Sabaté and Soret, 2014).

5.3.5 Conclusions

This section presented a methodology with a Water-Climate-Food Nexus for the development of the so-called SDG-Food index, which is based on five SDG-related food systems and their FLW generation. It is aimed to provide policy-makers with an understandable novel tool to highlight the level of compliance or non-compliance of any national, regional, or local FSC and FLW management system, for the development of decentralized policies based on each concrete context. It was considered four stages of the FSC and 11 FLW categories. Results of the Spanish case study highlighted a SDG-Food index value of 13.79, suggesting the food pillar as the most decisive one when developing future political strategies. Regarding the food categories, results suggested the categories of eggs, cereals, meat, and vegetables as better for compliance with the five SDG assessed. The stages of agricultural production and consumption seemed the highest index values if they were separately assessed. Moreover, a scenario of compliance with the Paris Agreement targets until 2040 presented better values for all stages, and a vegan diet was highlighted as the one with the best index score, followed by a vegetarian and a pescetarian diet. Future works on different FSC and FLW management systems could lead to comparative possibilities.

Additionally, a challenge that should be addressed in the future is the possibility of adding social aspects to this composite index. Nevertheless, there is an important problem with many composite indicators when they add together scores of environmental and social indicators, as they often make the implicit wrong assumption that environmental and social objectives can be substituted between them. Therefore, future work will be important to consider that more social work do not compensate for less environmental work, or vice versa. The same principle applies to each of the SDG, as each of the goals should be measured and they cannot be replaced by better values in other goals. Finally, the possibility of expanding this index to analyse regional and local contexts should also be considered.

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CHAPTER 6

General remarks and on-going research

6.1 General remarks

This Thesis has been articulated in six chapters, constituting the central chapters (from 2 to 6) the scientific basis that answer the hypotheses, objectives and sub-objectives presented. The methodology and the results contribute to facilitate the decision-making process for a correct management of the food losses and waste (FLW) in Spain.

The main scientific-technical contribution is the application of a methodology that connects life cycle thinking and the Water-Climate-Food Nexus, considering a circular economy approach. Although this methodology has been implemented in the management of FLW in Spain, it can be extrapolated to the food production and consumption system of other countries or regions. FLW throughout the supply chain have been quantified in terms of mass, energy, nutritional content and economic value.

i. The results obtained highlight the importance of considering all the stages of the supply chain, obtaining different FLW values in each of them for each food category considered. Similarly, the difference in the results according to the unit of measurement, that is in terms of mass, energy, nutritional or economic terms, is noteworthy. In general, fruit and vegetables losses and waste take a higher significance in terms of mass and nutritional content throughout the supply chain. However, for energy and economic losses, the highest values were found for the meat fraction, and especially in the domestic consumption stage.

ii. It becomes clear that the European waste hierarchy for FLW management, and in particular the reduction and management strategies on mass terms, and considering the entire supply chain, might not be the more efficient path. Therefore, the need to move towards a decentralization and diversification of the FLW management strategies is underlined, considering the particularities of each of the stages and of each of the different food categories.

iii. In particular, the results conclude that Spain characterized by a Mediterranean diet, needs to develop specific strategies for fruits and vegetables in the early stages of the supply chain, and for vegetable oils and meat in the end-of-life stages of the supply chain.

According to the FAO guidelines, the Water-Climate-Food Nexus approach has been applied throughout the food supply chain for the definition of FLW reduction strategies. This approach has been considered as the most appropriate to contribute to food security, food sovereignty, and the sustainability of the food system. The developed methodology has been applied to different FLW management strategies, particularly with regard to the management and end-of-life techniques.

i. The nutritional variable is significant for the definition of reduction and reuse strategies as secondary food, establishing the need to segregate the different fractions of FLW at source, especially in the early stages of the supply chain and for fruits and vegetables.

ii. The climate-energy variable has influence on the development strategies for energy and materials recovery, in which the selected technology is highly dependent on greenhouse gas (GHG) emissions and their potential contribution to climate change. In this sense, anaerobic digestion should be prioritized over “waste-to-energy” (incineration) and disposal technologies, whether the energy required for end-of-life operation is considered, or the energy and material credits obtained from these operations (in form of compost and gas) are contemplated.

iii. The study of the water variable included in the Nexus reinforced the results described for the climate-energy variable.

Considering the relative importance of the energy and water variables in the FLW end-of-life strategies, these indicators included in the Nexus have been evaluated for the two particular scenarios of compliance and non-compliance with the Paris Agreement. The interdependence between compliance with the Paris Agreement and the evolution of the energy mix in Spain in terms of GHG emissions has been studied.

i. Whether a compliance scenario is met or not, incineration technology is more intensive in GHG emissions than those ones obtaining gas and compost (anaerobic digestion and aerobic composting). Although, the prioritization of these last FLW management strategies is all the more important under a non-compliance scenario. The water variable does not present significant differences in decision-making regarding end-of-life technologies under the two frameworks considered. This fact stands out in the North of Spain and the islands.

ii. The FLW management in Spain is highly regionalized presenting as many scenarios as regions and associated treatment models. In this context, it is not possible to define from a technological and environmental point of view a common centralized strategy for all the FLW management in Spain. The solution is to establish harmonized guidelines and criteria that facilitate both the transition to a circular economy and the reduction of environmental impacts, especially those associated with global warming. To fulfill the European Union's landfill reduction targets, landfilling with energy recovery would increase the consumption of resources and the environmental impacts in the short and medium term. Those scenarios that include anaerobic digestion and aerobic composting have the lowest impacts, achieving the principles of the circular economy and being the most environmentally sustainable option. In this context, it is necessary to promote strategies that lead to the selective collection of FLW.

iii. Considering the potential impact of climate change on water resources in Spain, and in particular the heterogeneous availability of water between the Spanish regions, the analysis of the water variable of the Nexus could be significant under a scenario of compliance and non-compliance with the Paris Agreement. However, as end-of-life technologies are not very intensive in terms of water consumption and pollution, no significant differences have been found to define specific strategies in the different regions, with the exception of the water degradation assessment in a compliance framework, suggesting anaerobic digestion as the best option and incineration as the worst path.

To include the limits of growth in the decision-making process, the concept of sustainable degrowth was applied to the food supply chain. The aim is to introduce policies that meet food needs by reducing the consumption of resources and the environmental impacts. In parallel, a composite index so-called Sustainable Development Goals-Food index (SDG-Food index) has been developed for the evaluation of the FLW generation and management systems. The role of the index is to determine at national, regional or local contexts the level of compliance with five Sustainable Development Goals (addressing the problems of hunger in the world, food security, nutrition, availability and sustainable management of water, energy, sustainable consumption and production patterns, and climate change).

i. Degrowth strategies are essential to improve the environmental performance of food supply chains and FLW management options, establishing the limits of sustainable growth. The results highlighted the need to bet on a more vegetarian diet, beyond prioritizing local consumption, establishing a more seasonal diet and opting for organic farming. These four pillars have been considered to have the highest potential for reducing GHG emissions.

ii. Once again, the responsible consumption and the proper management of loss and waste from the meat, vegetables and fruit fractions are a priority path for the fulfillment of the Sustainable Development Goals evaluated. The categories of cereals, eggs and fish and seafood also stand out in this case.

The exceptional confinement measures imposed by the Spanish government as a consequence of the emerging coronavirus disease, COVID-19, have allowed the study of food production and consumption systems in Spain, as well as the generation and management of FLW in unusual conditions under a scenario of strong fluctuations and short-term changes in eating habits.

i. Although the COVID-19 pandemic denoted the strength of the Spanish food system, there is an opportunity to reorient and transform it towards higher resilience and sustainability.

ii. The COVID-19 pandemic has brought to light the importance of conducting an in-depth review of the soundness of the current food production and consumption systems in Spain. In particular, there is a need for a more flexible and local food distribution system. These measures allow the adaptability to unforeseen events, prioritizing local products and underlining the convenience of introducing tools that facilitate the interconnection of the different supply chains, as well as the introduction of measures to facilitate the donation and the use of FLW as secondary foods.

This Thesis is presented as a tool that allows an impartial and robust analysis to facilitate the decision-making of the generation and management of FLW. Under a life cycle thinking approach, and considering the principles of the circular economy, the management of FLW requires a strategic plan that include the productive sector, public administrations and consumers in the decision-making process.

Research and development should be strengthened in collaboration with the different actors in the food sector and research centers, playing a leading role and accompanying the future of the food system in Spain.

6.2 Conclusiones generales

Esta Tesis ha sido articulada en seis capítulos, entre los cuales, los capítulos centrales (del 2 al 6) constituyen la base científica para dar respuesta a las hipótesis, objetivos y sub-objetivos planteados. La metodología y los resultados presentados suponen una contribución a facilitar el proceso de toma de decisiones para una correcta gestión de las pérdidas y desperdicios alimentarios (PDA) en España.

La principal contribución científico-técnica es la aplicación de una metodología que conecta el pensamiento de ciclo de vida y el Nexo Agua-Clima-Alimentación, considerando un enfoque de economía circular. Si bien dicha metodología ha sido implementada en la gestión de las PDA en España, esta puede ser extrapolada al sistema de producción y consumo de alimentos de otros países o regiones. Se han cuantificado las PDA a lo largo de la cadena de suministro en términos de masa, energía, contenido nutricional y valor económico.

i. Los resultados obtenidos destacan la importancia de considerar cada una de las etapas de la cadena de suministro, obteniéndose distintos valores de las PDA en cada una de ellas para cada fracción de alimentos considerada. Del mismo modo, es reseñable la diferencia de resultados dependiendo de la unidad de medida considerada, es decir, si estas se miden en términos de masa, energéticos, nutricionales o económicos. En general, las pérdidas de frutas y verduras adquieren mayor significación en términos de masa y contenido nutricional en toda la cadena de suministro. Sin embargo, atendiendo a las perdidas energéticas y económicas, es la fracción carne y muy especialmente durante la etapa de consumo doméstico, la que representa la fuente de mayor perdida.

ii. Se pone de manifiesto que la jerarquía europea de actuación en materia de gestión de residuos de alimentos, y en particular las estrategias de reducción y gestión centradas en términos de masa y considerando de forma global toda la cadena de suministro, podría no ser la más eficiente, y por tanto se subraya la necesidad de caminar hacia la descentralización y diversificación de las estrategias de gestión, considerando las particularidades de cada una de las etapas y de cada una de las fracciones de alimentos consideradas.
iii. En particular, los resultados obtenidos concluyen que en España, con unos hábitos alimenticios caracterizados por una dieta Mediterránea, se precisa del desarrollo de estrategias específicas para frutas y verduras en las primeras etapas de la cadena de suministro, y para aceites vegetales y carne en las etapas de fin de vida de la cadena de suministro.

Se ha aplicado el enfoque de Nexo Agua-Clima-Alimentación a lo largo de la cadena de suministro de alimentos para la definición de estrategias de reducción de pérdidas de alimentos, en consonancia con las orientaciones de la FAO y considerando este enfoque como el más adecuado para contribuir a la seguridad alimentaria y a la sostenibilidad del sistema alimentario. La metodología propuesta ha sido aplicada a distintas estrategias de gestión de PDA, particularmente en lo referido a técnicas de gestión y fin de vida.

i. La variable nutricional cobra una especial significación para la definición de estrategias de reducción y reutilización como alimentación secundaria, estableciéndose la necesidad de segregar las distintas fracciones de residuos de alimentos en origen, muy especialmente en las primeras etapas de la cadena de suministro y para la fracción de frutas y verduras.
ii. La variable clima-energía es representativa en las estrategias relacionadas con la recuperación energética y de materiales, en las que la tecnología seleccionada tiene una destacada dependencia con las emisiones de gases de efecto invernadero (GEI) y su potencial contribución al cambio climático. En este sentido, las tecnologías de digestión anaerobia deben priorizarse a las tecnologías “waste-to-energy” (incineración) y vertido, tanto si se considera la energía necesaria para llevar a cabo la operación de fin de vida, como si se

consideran los créditos de energía y materia (en forma de compost y gas) obtenidos de dichas operaciones.

iii. El estudio de la variable agua incluida en el Nexo reforzó los resultados descritos para la variable clima-energía.

Considerando la importancia relativa de las variables energía y agua en las estrategias de fin de vida de las PDA, se han evaluado estas variables incluidas en el Nexo para los dos escenarios particulares de cumplimiento y no cumplimiento de los Acuerdos de Paris. Se ha estudiado la interdependencia entre el cumplimiento del Acuerdo de Paris y la evolución del mix energético en España en términos de emisiones GEI.

i. Tanto si se cumple un escenario de cumplimiento como si no, la incineración es más intensiva en GEI que aquellas conducentes a la obtención de gas y compost (digestión anaerobia y aerobia). Si bien, la priorización de estas últimas estrategias de gestión es tanto más importante bajo un escenario de no cumplimiento del Acuerdo de París. La variable agua no presenta diferencias significativas en la toma de decisiones relativa a las tecnologías de fin de vida bajo los dos escenarios considerados. Este hecho queda especialmente destacado en el caso de las regiones del norte de España y las islas.

ii. La gestión de las PDA en España está altamente regionalizada y presenta tantos escenarios como regiones y modelos de tratamiento asociados. En este contexto, no es posible definir desde un punto de vista tecnológico y medioambiental una única estrategia centralizada común para toda la gestión de las PDA en España más allá de establecer directrices y criterios armonizados que faciliten tanto la transición a una economía circular como la reducción de impactos ambientales, especialmente los asociados con el calentamiento global. En consonancia con el cumplimiento de los objetivos de reducción de vertederos de la Unión Europea, el vertedero con valorización aumentaría el consumo de recursos y los impactos ambientales en el corto y mediano plazo. Aquellos escenarios que incluyen digestión anaerobia y en menor medida compostaje presenta los menores impactos, cumpliendo con los principios de la economía circular y son, además, la opción más sostenible desde el punto de vista medioambiental. En este contexto general, es necesario promover estrategias que conduzcan a la recogida selectiva de las PDA.

iii. Considerando el potencial impacto del cambio climático en los recursos hídricos en España, y en particular la heterogénea disponibilidad de agua entre las diferentes regiones de España, el análisis de la variable agua del Nexo en la gestión de las PDA podría ser significativo bajo un escenario de cumplimiento y no cumplimientos de los Acuerdos de Paris. Sin embargo, y revelándose las tecnologías de fin de vida consideradas como poco intensivas en consumo y contaminación de agua, no se han encontrado diferencias significativas que conduzcan a estrategias diferenciadoras entre las distintas regiones, con la excepción del análisis de la degradación del agua en un marco de cumplimiento, que sugiere la digestión anaeróbica como la mejor opción y la incineración como la peor vía.

De manera transversal, y con el objetivo de realizar una aproximación que tenga en cuenta los límites del crecimiento en la toma de decisiones, se ha incluido el concepto de decrecimiento sostenible aplicado a la cadena de suministro de alimentos con la finalidad de introducir políticas capaces de satisfacer las necesidades alimentarias reduciendo además de los impactos ambientales, también el consumo de recursos. En paralelo, se ha propuesto un índice compuesto para la evaluación de los sistemas de generación y gestión de PDA, el denominado Índice de Objetivos de Desarrollo Sostenible-Alimentos (SDG-Food index), cuyo fin es determinar el nivel de cumplimiento de cualquier contexto nacional, regional o local concreto con respecto a cinco Objetivos de Desarrollo Sostenible (abordando las problemáticas del hambre en el mundo, la seguridad alimentaria, la nutrición, la disponibilidad y la gestión sostenible del agua, la energía, los patrones de consumo y producción sostenibles, y el cambio climático).

i. Para la mejora del desempeño ambiental de las cadenas de suministro de alimentos y las opciones de gestión de las PDA, estableciendo los límites de un crecimiento sostenible, es necesario aplicar estrategias de decrecimiento. Los resultados obtenidos apuntan a la necesidad de apostar en primer lugar por una dieta más vegetariana, además de priorizar el consumo local, establecer una dieta más estacional y apostar por una agricultura ecológica. Estos cuatro pilares han sido considerados como los de mayor potencial de reducción de las emisiones de GEI.

ii. De nuevo el consumo y la correcta gestión de las PDA de carne, verduras y frutas se erige como vía prioritaria para el cumplimiento de los Objetivos de Desarrollo Sostenible evaluados, destacando en este caso también las categorías de cereales, huevos y los pescados y mariscos.

Las excepcionales medidas de confinamiento impuestas por el gobierno español como consecuencia de la enfermedad emergente del coronavirus, COVID-19, han permitido el estudio de los sistemas de producción y consumo de alimentos en España, así como de la generación y gestión de los PDA en condiciones excepcionales bajo un escenario de fuertes fluctuaciones y cambios a corto plazo en los hábitos alimentarios.

i. Aunque la pandemia del COVID-19 ha puesto de relieve la fortaleza del sistema alimentario español, existe la oportunidad de reorientarlo y transformarlo para que sea más resiliente y sostenible.

ii. La pandemia del COVID-19 ha subrayado la relevancia de realizar una revisión profunda sobre la solidez de los sistemas actuales de producción y consumo de alimentos en España. En particular, se constata la necesidad de un sistema de distribución de alimentos más flexible y próximo que permita la adaptabilidad ante imprevistos, priorizando los productos locales y subrayando la conveniencia de establecer herramientas que faciliten la interconexión de las diferentes cadenas de suministro, así como la introducción de cuantas medidas sean necesarias para facilitar la donación y el aprovechamiento de las PDA como alimentos secundarios.

Esta tesis doctoral se presenta como una herramienta que permite un análisis objetivo y robusto que contribuye a facilitar la toma de decisiones en torno a la generación y gestión de las PDA. Bajo un enfoque de pensamiento de ciclo de vida, y teniendo en cuenta los principios de la economía circular, la gestión de las PDA requiere un plan estratégico en cuyo proceso de toma de decisiones debe participar el sector productivo, las administraciones públicas y los consumidores.

La investigación y el desarrollo pueden y deben reforzarse en colaboración con los distintos componentes del sector alimentario y los centros de conocimiento, desempeñando un papel de liderazgo y acompañando el futuro del sistema alimentario en España.

6.3 On-going research

Despite the contributions described in the Thesis, there are still innovative challenges ahead that must be overcome to improve the present research. Among them, the need for assessing the socio-economic aspect of FLW management strategies to provide the decision-making process with the three pillars of sustainability. These elements should be balanced, i.e., more environmental sustainability cannot substitute socio-economic aspects, and vice versa. A first approach to the social evaluation has already been made with the degrowth assessment. Nevertheless, certain variables, such as previous and future investment in waste infrastructure, maintenance of the installations and transport distances of FLW, may be decisive when thinking on developing or not potential new strategies of FLW management.

In this context, a research under development is aiming to include a life cycle costing approach to the Water-Climate-Food Nexus results obtained in this Thesis. Therefore, the prices of different FLW management options are being assessed: i) landfill, ii) incineration, iii) aerobic composting, and iv) anaerobic digestion. Additionally, the existing taxes at any FLW management option and Spanish region, the national and European landfill restrictions, and the projected evolution of the CO_2 prices until 2040, are being tabulated. This study aims to link the assessment of the environmental, social and economic sustainability in the Spanish food sector, for providing a holistic approach when developing regionalized FLW management policies in Spain, and moving from national to regional approaches when designing future roadmaps.

6.4 Progreso de la investigación

A pesar de las contribuciones descritas en esta Tesis, aún quedan por delante retos innovadores que deben abordarse para mejorar la presente investigación. Entre ellos, la necesidad de evaluar el aspecto socioeconómico de las estrategias de gestión de las PDA para dotar al proceso de toma de decisiones de los tres pilares de la sostenibilidad. Estos elementos deben estar equilibrados, es decir, una mayor sostenibilidad ambiental no puede sustituir los aspectos socioeconómicos y viceversa. Ya se ha realizado un primer acercamiento a la evaluación social mediante el análisis del decrecimiento. No obstante, determinadas variables, como la inversión previa y futura en infraestructura de residuos, el mantenimiento de las instalaciones y las distancias de transporte de las PDA, pueden ser determinantes a la hora de pensar en desarrollar o no posibles nuevas estrategias de gestión de las PDA.

En este contexto, una investigación actualmente en desarrollo tiene como objetivo incluir un enfoque de análisis económico del ciclo de vida aplicado a los resultados del Nexo Agua-Clima-Alimentación obtenidos en esta Tesis. Para ello, se están evaluando los precios de diferentes opciones de manejo de las PDA: i) vertedero, ii) incineración, iii) compostaje aerobio y iv) digestión anaerobia. En este sentido, se están inventariando los impuestos existentes en cualquier opción de gestión de las PDA y cada región española, las restricciones de vertido nacional y europeo, y la evolución proyectada de los precios de emisión de CO_2 hasta 2040. Este estudio tiene como objetivo vincular la evaluación de la sostenibilidad ambiental, social y económica en el sector alimentario, para proporcionar un enfoque holístico al desarrollar políticas de gestión de las PDA regionalizadas en España, pasando de enfoques nacionales a regionales en el diseño de futuras hojas de ruta.

ANNEXES

Supplementary material and dissemination

A1. Supplementary material of Chapter 2

Contents:

Section A1.1

- **Table A1.1** Food commodities included in the study.
- **Table A1.2** Food balance sheet (FBS) for Spain in 2015. All values in 1000 tons.
- **Table A1.3** Summary table with main sources of data information.
- **Table A1.4** Conversion factors for the allocation of ingredients to the corresponding category or the transformation of food items into raw commodity equivalents.
- **Table A1.5** Prices at origin, wholesale and consumer level for the food categories under study.
- **Table A1.6** Proteins, carbohydrates and energetic content for the food categories under study (Bedca, 2017).
- **Table A1.7** Unavoidable FLW percentages for each food category as a percentage of what enters in each supply chain stage.
- **Figure A1.1** Outline of the assumed division in stages of the food supply chain.
- **Table A1.8** Mass-to-energy conversion factors and life cycle inventory sources.
- **Table A1.9** Results in petajoules per year in Spain of the primary energy demand by each food category under study, and on each food supply chain stage. The values are related to the percentages assumed, based on Laso et al. (2018).

- **Table A1.10** Results in MJ day-1 cap-1 of the embodied energy loss and in kJ day-1 cap-1 of the food energy loss by each food category under study, on each stage.
- **Table A1.11** Allocation and conversion factors used for calculating the edible part of food production, which is used for human consumption (Gustavsson et al., 2013).
- **Table A1.12** Food losses and waste percentages for each food category as a percentage of what enters on each supply chain stage. Unless stated otherwise, percentages are obtained from Section 2.1 and Gustavsson et al. (2013) for Europe region.
- **Table A1.13** Results of the Energy return on investment – Circular economy index on fish and seafood, cereals, vegetables and meat, on each of the considered scenarios.

Table A1.1 Food commodities included in the study.

Food category	Commodities included
Cereals	Wheat, rice, maize, others
Roots & tubers	Potatoes
Sugar	Sugar
Vegetable oils	Sunflower oil, palm oil, olive oil, others
Vegetables	Tomatoes, onions, other
Fruits	Oranges and mandarins, grapes (excluding wine), apples, others
Pulses	Beans, peas, others
Meat & animal fat	Bovine meat, mutton and goat meat, pig meat, poultry meat
Fish & seafood	Fish and seafood
Dairy products	Milk, cheese, butter
Eggs	Eggs

The domestic supply estimated includes the total production, but the assessment of the FLW only considers the fraction of the total production directed to human food. For cereals, production, stock, feed and seed values as well as postharvest losses were retrieved from the balance sheets built up by the Spanish Ministry (MAPAMA, 2017a). For sugar, production values were gathered from the European working document (EC, 2016). For vegetable oils, industrial production data were taken from the Statistics on industrial production and international trade (Eurostat, 2015e). Production and utilization elements of dairy products category were also taken from the Spanish statistics of production and destination of milk in farms (MAPAMA, 2017b). For fish and seafood, total production is taken from Spanish statistics (MAPAMA, 2017c) and is the sum of the maritime catches and aquaculture (excluding hatcheries and nurseries) production. The share of utilization elements was taken from the aquaculture statistic by final destination and the same distribution for utilization of fish and seafood maritime catches was assumed. For the rest of categories, production values were mainly sourced from Eurostat (2015a, 2015b, 2015c, 2015d). The relative percentages reported in FAOSTAT datasheets (FAO, 2015) were used to estimate the part of the total production intended for human consumption when no data were found for 2015, as well as the fractions addressed to the rest of utilization elements. Finally, national stock data were obtained from FAOSTAT database

(FAO, 2015) and assumed similar to the food availability in 2013. For international trade, both fresh and manufactured products were taken into account. Food categories were modelled at the level of ingredients to avoid double counting of ingredients. For food items showing more than one ingredient, each ingredient has been allocated to the corresponding category. Conversion factors for ingredient equivalents are shown in Table A1.2.

The four different assessed diets are described as follows:

i) A vegetarian diet includes cereals, roots, sugar, vegetable oils, vegetables, fruits, pulses, dairy products, and eggs.
ii) A pescetarian diet is a vegetarian diet that includes fish and seafood.
iii) A Mediterranean diet is similar to the pescetarian, but includes moderate amounts of meat.
iv) Omnivorous diets consider all food groups.

Table A1.2 Food balance sheet (FBS) for Spain in 2015. All values in 1000 tons.

	Domestic supply						Domestic utilization			
	Prod.	**Import**	**Stock**	**Export**	**Waste[1]**	**Total**	**Food (p.)[2]**	**Food (f.)[3]**	**Feed**	**Seed & other Use**
Cereals	19,699	16,871	3,908	1,418	104	38,956	7,925	0	27,694	3,337
Roots & tubers	2,284	1,016	113	373	111	2,928	1,739	641	111	437
Sugar	512	1,978	-53	456	0	1,981	1,966	0	0	15
Vegetable oils	3,912	1,987	-601	1,024	0	4,273	1,944	0	0	2,328
Vegetables	12,788	1,213	78	6,226	1,153	6,701	3,805	2,536	360	0
Fruits	12,548	1618	-205	7,095	1,357	5,509	3,461	2,023	11	14
Pulses	503	373	30	112	41	753	236	157	293	66
Meat & animal fat	6,053	479	0	658	0	5,874	5,874	0	0	0
Fish, Seafood	1,258	51	6	40	0	1,275	1,230	44	0	1
Dairy products	8,105	945	0	519	0	8,531	6,342	0	1,695	494
Eggs	2,040	31	13	167	42	1,875	1,734	0	3	139

(1) Refers to the amounts of commodity lost during handling, storage and transport between supply and utilization, i.e. postharvest and storage stage. Losses occurring during the pre-harvest and harvesting stages are excluded from this table.

(2) Refers to the part of the commodity intended to human consumption after processing and/or packaging. It is thus the input to the processing and packaging stage.

(3) Refers to the part of the commodity used directly fresh. This flow is directly addressed to distribution stage.

A summary of the main sources of information is presented below:

Table A1.3 Summary table with main sources of data information.

Data	Data specific to country/region	Year	Reference
Cereals production, stock, feed and seed, postharvest losses	Spain	2015	MAPAMA (2017a)
Sugar production	Spain	2015	EC (2016)
Vegetable oils industrial production	Spain	2015	Eurostat (2015e)
Dairy production and utilization	Spain	2015	MAPAMA (2017b)
Fish production and utilization	Spain	2015	MAPAMA (2017c)
International trade	Spain	2015	DataComex (2018)
Remaining production data	Spain	2015	Eurostat (2015a, 2015b, 2015c, 2015d)
Remaining stock and utilization data	Spain	2013	FAO (2015)
Agricultural production losses for cereals, roots & tubers, sugar, vegetable oils, vegetables, fruits and pulses	Spain	2011	MAPAMA (2013a)
Postharvest losses percentages	Spain	2013	FAO (2015)
Processing losses for cereals, roots & tubers, meat and dairy products percentages	Spain	2011	MAPAMA (2013b)
Remaining food losses and waste percentages, allocation factors and fresh factors	Europe	2011	Gustavsson et al. (2013)

Table A1.4 Conversion factors for the allocation of ingredients to the corresponding category or the transformation of food items into raw commodity equivalents.

Food item	Main ingredients (conversion factor)	References, comments
Bread	Wheat flour (0.7)	Nielsen et al. (2003). Same conversion factor assumed for cake and pastry products, waffles and wafers.
Pasta	Wheat flour (0.94)	Bevilacqua et al. (2007).
Pasta-containing egg	What flour/eggs (0.84/0.16)	Gallo (2018). Three eggs per kg of pasta. Assumed average of not in shell eggs: 54 g.
Biscuits	Other cereals/sugar (0.37/0.26)	Noya et al. (2017). Modelled as gluten-free biscuits.
Sugar beet	Sugar (0.14)	FAO (1972). Technical factors from FAO used to estimate sugar (raw equivalents).
Sugar cane	Sugar (0.08)	FAO (1972). Technical factors from FAO used to estimate sugar (raw equivalents).
Cocoa powder	Sugar (0.025-0.9)	Datacomex (2018). Trade flows in the database specified the content of sugar.
Tomato sauce	Tomato (1.0)	Del Borghi et al. (2014). Tomato sauce contains on average 1.77 kg tomato/kg sauce. To avoid overestimation of FLW, 1.0 is assumed. Same factor assumed for fruit juices based on the same justification.

For the economic FLW calculation, the following data were used:

Table A1.5 Prices at origin, wholesale and consumer level for the food categories under study.

	Production (€/kg)	Wholesale (€/kg)	Retail (€/kg)
Cereals	0.2	0.2	1.0
Roots & tubers	0.3	0.4	1.0
Sugar	0.0	0.4	0.8
Vegetable oils	1.8	2.2	2.7
Vegetables	0.3	0.6	1.5
Fruit	0.4	1.0	1.7
Pulses	1.6	2.0	3.5
Meat & animal fat	2.7	3.4	7.2
Fish & seafood	0.6	0.7	1.0
Dairy products	0.3	0.6	0.8
Eggs	2.5	3.8	7.0

For the nutritional FLW calculation, the following data were used:

Table A1.6 Proteins, carbohydrates and energetic content for the food categories under study (Bedca, 2017).

	Proteins (%)	Carbohydrates (%)	Kcal (per 100 g)
Cereals	10	84	362
Roots & tubers	12	85	73
Sugar	0	0	408
Vegetable Oils	0	0	887
Vegetables	18	80	22
Fruits	4	95	51
Pulses	29	65	303
Meat	50	0	164
Fish & seafood	89	0	83
Dairy products	19	29	65
Eggs	34	0	150

For the avoidable and unavoidable FLW calculation, the following data were used:

Table A1.7 Unavoidable FLW percentages for each food category as a percentage of what enters in each supply chain stage.

	Agricultural production	Postharvest handling & storage	Processing & packaging		Distribution		Consumption	
			Milling	Proc.	Fresh	Proc.	Fresh	Proc.
Cereals (%)	2.00	0.50	0.50	3.50	2.00	2.00	1.00	1.00
Roots & tubers (%)	6.59	4.50		10.00	3.00	2.00	2.00	1.00
Sugar (%)	6.6	0.00		2.00	8.00	2.00	5.00	1.00
Vegetable oils (%)	6.00			5.00	1.00	1.00	1.00	1.00
Vegetables (%)	6.00	4.00		2.00	8.00	2.00	1.00	1.00
Fruits (%)	6.51	4.00		2.00	8.00	2.00	5.00	1.00
Pulses (%)	6.00	0.00		2.00	1.00	1.00	1.00	1.00
Meat (%)	3.10	0.00		5.00	4.00	4.00	2.00	2.00
Fish & seafood (%)	5.70	0.00		6.00	9.00	5.00	2.00	1.00
Dairy products (%)	3.50	0.00		0.10	0.50	0.50	0.10	0.10
Eggs (%)	4.00	0.00		0.10	0.20	0.20	1.00	1.00

The most significant source of uncertainty in Section 2.1 is due to the loss percentages used for the calculations. Data used from Gustavsson et al. (2013) are for Europe region and differences among countries are not considered. They are the best currently available and have been assumed to be generalizable and extrapolated. Nonetheless, although they are considered a good reference for this work, they may lead to errors when they are assumed for a specific country. For this reason, they have been updated with Spanish data when possible.

This study assumes that there is no discrepancy between domestic supply and domestic utilization (sold production + imports – exports) and, consequently, all goods sold and all imports are consumed, following FAOSTAT approach. The accuracy of the resulting balance sheet depends on the availability and reliability of the underlying basic statistics of production, supply and utilization of foods and population statistics. Official production data are sometimes questionable: farmers often equate production with tax collection and information on losses causes by pests and diseases, during storage, transportation and on quantities intentionally discarded for the purpose of price control are usually not available. Other limitations are that non-commercial production are usually not included and might be an appreciable part of total production and there are also problems related to the time-reference period to be used in preparing food balance sheets (FAO, 2018).

Due to the methodology used, which developed data by a mass flow model, the uncertainty regarding FLW builds up along the chain. A significant gap between the statistical data of production sold in the industry and consumption data according to MAPAMA (2015a) is observed, which can be due to methodological differences such as different product classifications, external trade records movement of goods across borders and the lack of distinction between imports and exports involving sales from other flows. Furthermore, the surveys have different thresholds for the minimum size of enterprise that can be surveyed while only 12,000 household consumers are surveyed by MAPAMA recording their daily purchases. Different approaches are being addressed to improved national statistical integration across agencies. One is the Loss-Adjusted Food Availability (LAFA) data series at the United States Department of Agriculture (USDA), which provides the estimates food availability for human consumption after adjusting for food spoilage and other losses (ERS, 2017). Total food supply is adjusted to incorporate exports, imports and stocks, providing total food availability data, as in FAO procedure. Later, food availability data is adjusted to account for three loss factors (i.e.: primary production, retail and consumer level). Saving the differences of each methodology, FLW is difficult to be measured accurately at the consumer level as participants in household surveys on FLW tend to be highly "reactive", changing their behavior during the survey period instead of acknowledging how much food they typically discard or misstating their true levels of discarded food products (ERS, 2017). Although the data tend to indicate that food balance sheets might overestimate food availability, household surveys may underestimate food processed in the hospitality sector (Kirkendall, 2015). In fact, a daily consumption (not intake) of 1,600 kcal is estimated for an average Spanish citizen (MAPAMA, 2015a), which deterred us of using those data.

Finally, the described minimum scenario is an idealization of the minimum FLW achieved in other regions as stated by Kummu et al. (2012). These loss and rates could be unfeasible in the country under study owing to geographical differences or economic, political, and social factors. For example, reducing FLW in the FSC could involve transfer mechanisms and trade-off for other stakeholders, being inefficient in economic terms (Chaboud and Daviron, 2017). On the other hand, avoidable FLW may differ from one country to another, based on cultural, religious, and personal preferences related to what is considered edible. Political and regulatory framework may also constrain the potential to reduce FLW (Kummu et al., 2012). Besides, the estimates of this work through an MFA along the FSC, are considered trustworthy based on the previous comparison and validation with other studies.

For the PEDd calculations in Section 2.3, based on the developed methodologies in several previous studies to perform the PED, mainly the works developed by Vittuari et al. (2016), Infante-Amate et al. (2013), and Cuellar and Webber (2010), the FSC was divided into four different stages: agricultural production, processing and packaging, distribution and consumption (Figure A1.1). The methodology of this work, started by calculating the PED of the entire Spanish supply chain in 2015, followed by the calculation of the EEL and the FEL, ending by the calculation of the novel index so-called $EROI_{ce}$. All data utilized and elaborated in this work were referred to Spain, with the exception of some mass-to-energy factors, which have been taken from the literature or Thinkstep's Database (2017) and were assumed as internationals (Table A1.8). It was tried to develop a consistent inventory, with approaches to quantification and assumptions that would allow to make it comparable with other similar studies in the future. It was intended to maintain a huge transparency related to the information obtained, the procedures and the assumptions.

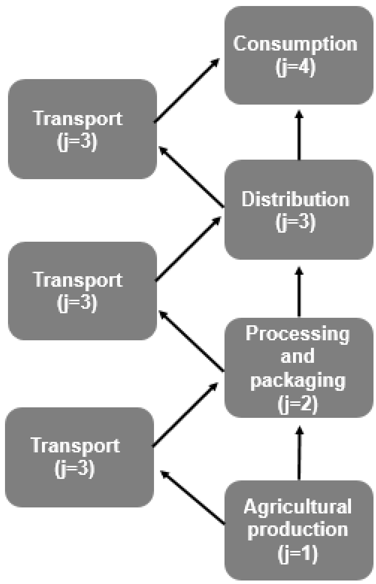

Figure A1.1 Outline of the assumed division in stages of the food supply chain.

PED values for each category and stage are firstly calculated in petajoules (PJ) per year in Spain and transformed to the functional unit (kJ day^{-1} cap^{-1}). It has been used a mass-to-energy conversion factor obtained from the division between the petajoules of each category of food in the agricultural stage between the tons of mass production values. To obtain the percentages corresponding to each food category, a proportion based on Laso et al. (2018), was used. Those values are divided first by the Spanish population in 2015 (46,528,966 persons) and secondly by the 365 days of the year.

The PED calculated in the agricultural production stage includes i) consumption of fuel for traction, irrigation, heating and drying, and ii) electrical energy for mechanical operations and lighting. Data were obtained from the Ministry of Agriculture and Fisheries, Food and Environment of Spain (MAPAMA, 2015) and the Spanish Institute for the Diversification and saving of Energy (IDAE, 2015). On the other hand, it is considered the indirect energy use necessary for the production of i) machinery, ii) fertilizers, iii) pesticides and iv) plastic materials used in agriculture. The number of existing machineries for agricultural production in Spain during the reference period (2015) was retrieved for the statistical yearbook of the Ministry of agriculture of Spain (MAPAMA, 2015). To make a representative calculation of the weight of the machinery, it is used as a reference for each of the three categories of the yearbook (tractors, automotive machineries, trailers) the weight of one of the most sold models. To calculate the energy used in the construction and maintenance of the machinery, a mass-to-energy factor from Thinkstep's Database (2017) was used (Table A1.8). For calculating the energy used in the production of fertilizers and treatments, the statistical data of the amount of fertilizers and pesticides consumed, extracted from the Department of Agriculture and Fishery, Food and Environment (MAGRAMA, 2015), were also considered. The different types of fertilizers used are added in three large groups: i) nitrogenous, ii) phosphate and iii) potassium. The different types of pesticides used are grouped into: i) fungicides, ii) herbicides, iii) insecticides and iv) molluscicides. For the group of molluscicides no specific factor was found, but it is assumed as acceptable to use the same as for insecticides. The use of plastic material in agriculture is deduced through the Department of Agriculture and Fishery, Food and Environment (MAGRAMA, 2015), considering the m^3 of i) quilting, ii) tunnels and iii) fixed installations. To move from m^3 to tons, the weight data of plastics in agriculture in Spain for the year 2015 has been used (ANAIP, 2015). The mass-to-energy conversion factors for each group has been extracted from Thinkstep's Database (2017) (Table A1.8). The energy used in the production of feed for livestock was calculated by multiplying the amount of average consumption obtained by the Spanish statistical yearbook (MAGRAMA, 2015) and multiplied by a mass-to-energy factor of Infante-Amate et al. (2014), as represented in Table A1.8.

The PED for mechanical processes, cooking, freezing, and space heating/cooling during food processing, and the indirect energy use for packaging of products, has been taken into account. PED related to the food industry has been retrieved from the Spanish Institute for the Diversification and Saving of Energy (IDAE, 2015), transforming the ktep of each type of fuel to kJ, converting final to primary energy by using the updated transformation table for 2015. The energy use for packaging has been obtained by adding the energy use to produce i) plastics, ii) glass, iii) paper and cardboard and iv) light metal packaging. The energy used in wood and cork packaging is not considered as its proportional fraction is minimal. The production data of plastic packaging are extracted from the Spanish Association of Plastics Industry (ANAIP, 2015) and the Department of Agriculture and Fishery, Food and Environment (MAGRAMA, 2015). The production data of glass packaging has also been taken from the Department of Agriculture and Fishery, Food and Environment (MAGRAMA, 2015). The production data of paper and cardboard packaging has been taken from the Spanish Association of Pulp, Paper and Cardboard Manufacturers (ASPAPEL, 2018), and a proposed percentage of use for the food industry (42%), as well as the mass-to-energy conversion factor (Table A1.8) are extracted from Infante-Amate et al. (2014). The production data of light metal packaging have been found in Metal Packaging Europe (2018). A proposal for the percentage use of light metal packaging in the food industry in Spain (77%), as well as a proposal to perform the energy analysis based on the composition in aluminum (7%) and steel (93%), and its consequent mass-to-energy factors; are obtained from the magazine specialized in informing about the life cycle of packaging (INFOPACK, 2018), as represented in Table A1.8.

In this stage it has been decided to include i) the transport of food products and ii) the distribution in food stores, accommodations and restaurants. According to Neira et al. (2014), an important part of the discussion on sustainability in the FSC lies in the first part of this stage, related to the energetic cost of transporting food products throughout the chain. For developing the energy balance, firstly the national road transport associated with the FSC was first taken into account. For the estimation, the data of agriculture products, fish and other fishing products, and food products, beverages and tobacco; of the Ministry of Development of Spain (MAGRAMA, 2015), have been considered. The energy intensity value for road transport is taken from Pérez-Martínez and Monzon (2009) (Table A1.8). Besides, the energy of transporting imported products is calculated, by using Datacomex basis data (2018), and 10 food categories are considered, excluding only the categories of beverages and tobacco. Transportation by boat, train, road and plane are analyzed. It has been used masses-distance products (t-km) coming from Simon-Fernandez et al. (2014) and Pérez-Martínez and Monzón (2009), for i) international boat transportation, ii) international train transportation, iii) international road transportation and iv) airplane transportation (Table A1.8). Finally, the transport of consumers to go shopping has been also taken into account. It is assumed that all products are bought at the same time, and therefore the emissions of diesel consumption are divided by each product. This part needs to be highly assumed since little information is available on how Spanish people get and consume food products. For developing this information, the per capita consumption in Spain in one year in kg was extracted from the Department of Agriculture and Fishery, Food and Environment (MAGRAMA, 2015). As it is estimated that 59% of the population goes shopping on foot, 35% by car and 4% using public transportation (MAGRAMA, 2015), it could be extracted the kg that have been bought by car and bus. According to the methodology of I Canals et al. (2007), to make the purchase by car, about 0.185 Km/Kg are transported, and when going by bus, about 0.00085 Km/Kg are transported. Through this assumption, the km travelled could be obtained related to the total purchases made by car and bus by the Spaniards. According to IDAE (2015), a car consumes 8 liters of fuel every 100 km travelled, and a bus consumes 40 liters of fuel every 100 km travelled. Through these assumptions, it is extracted the data of fuel liters used to make the purchase. It has been searched the number of vehicles registered in Spain with diesel and gasoline consumption, as well as the energy factor of each of the two fuels in 2015. Finally, these two energy values were added in a single one. For the distribution part it has been considered i) the energy that has been used in the distribution of food in wholesale and retail in Spain. For obtaining that information, it has been considered energy consumption data from the IDAE (2015) which were taken into account for each reference year, and transformed from ktep to kJ. On the other hand, ii) the energy used in the production of food in restaurants and accommodation, which has been also taken from IDAE (2015), is added to the data of this stage. Both kind of data were transformed from final energy to primary energy by using the updated transformation tables for each year.

As the energy associated with the distances and types of transportation to buy food for households' consumption was already analyzed, this stage considers only the energy used in the preparation and maintenance of food at homes. Energy consumption data from the IDAE (2015) are considered, which have been transformed from ktep to kJ, and again from final energy to primary energy. From all the data in IDAE (2015), only the categories of home appliances and electricity for cooking, are considered. From the first category, a factor extracted from Infante-Amate et al. (2014) was used, which states that only 40% of the totality of home appliances are used for cooking food.

Table A1.8 Mass-to-energy conversion factors and life cycle inventory sources.

	Energy-to-mass factor (MJ/Kg)	Source
Agricultural production		
Direct energy use		
Agriculture (fuel)		(IDAE, 2015)
Agriculture (electricity)		(IDAE, 2015)
Fisheries (fuel)		(IDAE, 2015)
Indirect energy use		
Machinery	27.6	(Thinkstep, 2017, MAGRAMA, 2015, IDAE, 2015)
N fertilizers	68.06	(Thinkstep, 2017, MAGRAMA, 2015)
P fertilizers	34.47	(Thinkstep, 2017, MAGRAMA, 2015)
K fertilizers	4.03	(Thinkstep, 2017, MAGRAMA, 2015)
Fungicides	237.7	(Thinkstep, 2017, MAGRAMA, 2015)
Insecticides	239.4	(Thinkstep, 2017, MAGRAMA, 2015)
Molluscicides	351.2	(Thinkstep, 2017, MAGRAMA, 2015)
Quilting	69.7	(Thinkstep, 2017, ANAIP, 2015)
Tunnels	72.6	(Thinkstep, 2017, ANAIP, 2015)
Fixed installations	63.6	
Food processing and packaging		
Direct energy use		
Fuel use		(IDAE, 2015)
Electricity		(IDAE, 2015)
Indirect energy use		
Glass		(Infante-Amate et al., 2014, MAPAMA. 2015)
Plastic	15.5	(Infante-Amate et al., 2014, ANAIP. 2015)
Paper and cardboard	77.7	(Infante-Amate, 2014, ASPAPEL. 2018)
Aluminum	18.4	(Infante-Amate, 2014, Metal Packaging Europe)
Steel	46.3	(Infante-Amate, 2014, Metal Packaging Europe)
Distribution	27.5	
National road transportation		(MAGRAMA, 2015, Perez-Martínez and Mozon, 2009)
International boat transportation	0.4	(MAGRAMA, 2015, Perez-Martínez and Mozon, 2009, Simón-Fernández et al., 2014)
International train transportation	0.2	(Perez-Martínez and Mozon, 2009, DataComex, Simón-Fernández et al., 2014)
International road transportation	0.3	(Perez-Martínez and Mozon, 2009, DataComex, Simón-Fernández et al., 2014)
Airplane transportation	2.1	(MAGRAMA, 2015, Perez-Martínez and Mozon, 2009, Simón-Fernández et al., 2014)
Transportation to purchase	21.0	(MAPAMA, 2015, IDAE, 2015, I Canals et al., 2007)
Restaurants and accommodation		(IDAE, 2015)
Storage		(IDAE, 2015)
Consumption		
Home appliances		(IDAE, 2015)
Electricity cooking		(IDAE, 2015)

Table A1.9 Results in petajoules per year in Spain of the primary energy demand by each food category under study, and on each food supply chain stage. The values are related to the percentages assumed, based on Laso et al. (2018).

	%	**Agric. prod.**	**Proc. & pack.**	**Distribution**	**Consumption**
Cereals	13.9	74.5	48.1	85.7	32.8
Roots	1.7	9.0	5.8	10.4	4.0
Sweets	0.1	4.3	2.8	4.9	1.9
Vegetable oils	3.6	19.7	12.7	22.6	8.7
Vegetables	16.9	90.4	58.3	104.0	39.8
Fruits	3.5	18.9	12.2	21.8	8.3
Pulses	2.5	13.4	8.7	15.5	5.9
Meat	28.0	149.8	96.7	172.4	66.0
Fish and seafood	16.3	86.9	56.1	100.0	38.3
Dairy products	7.2	38.7	25.0	44.5	17.1
Eggs	5.4	29.0	18.7	33.4	12.8
TOTAL		534.7	345.0	615.2	235.7

Once the percentages of PED on each stage were distributed between each food category, the EEL and FEL were calculated. EEL was calculated through primary energy demand data. FEL was calculated throw the mass losses along the food supply chain, transforming the data in nutritional energy, through the factors of the Bedca Database (2017), as shown in A1.6. For performing the MFA and the energy flow analysis, it has been used the allocation and conversion factors of Gustavsson et al. (2013) for each food category. It is considered only the part of the production that is considerate edible and used for human consumption.

EEL and FEL are in both cases calculated using mass-loss factors obtained from the work developed in Section 2.2, and Gustavsson et al. (2013). The calculation of the energy losses of the stages of food processing and packaging, distribution and consumption, is based on the food mass and energy production values of the previous stage, to which the mass and energy loss of the previous stage of each category is subtracted. The values have been relativized in every stage according to the already mentioned mass-to-energy calculated factor. Results are shown in A1.10:

Table A1.10 Results in MJ day^{-1} cap^{-1} of the EEL and in kJ day^{-1} cap^{-1} of the food energy loss by each food category under study, on each stage.

	Agricultural production		Processing and packaging		Distribution		Consumption	
	EEL*	FEL**	EEL*	FEL**	EEL*	FEL**	EEL*	FEL**
Eggs	1.6	209.3	0.2	799.7	1.3	104.7	5.8	1,285.3
Meat	3.3	92.1	10.6	598.7	13.4	71.2	41.2	83.7
Fish and Seafood	4.5	71.2	5.8	16.7	12.9	29.3	21.8	12.6
Dairy products	1.4	184.2	0.1	4.2	0.4	16.7	6.8	104.7
Cereals	0.8	209.3	4.8	799.7	3.3	104.7	46.6	1,272.8
Sweets	0.4	37.7	0.1	37.7	0.2	37.7	2.0	284.7
Pulses	0.4	29.3	0.7	8.4	0.5	16.7	5.6	46.1
Vegetable oils	0.5	276.3	1.1	213.5	0.4	41.9	2.0	159.1
Vegetables	11.8	100.5	1.9	4.2	2.4	16.7	37.4	54.4
Fruits	2.5	230.3	0.4	8.4	0.5	33.5	7.8	104.7
Roots	0.9	46.0	1.6	46.1	0.4	16.7	2.7	50.2

*Embodied energy loss is represented in MJ/cap/day
**Food energy loss is represented in kJ/cap/day

Allocation factors were used to determine the part of the agricultural product intended to human consumption. It is only used for estimating FLW in agricultural production and postharvest stages, since the rest of losses are calculated once the food addressed to human consumption is derived from Equation 2.6. These factors were calculated from A1.11. For food categories not reported that table, allocation factor equal to unity were assumed.

Table A1.11 Allocation and conversion factors used for calculating the edible part of food production, which is used for human consumption (Gustavsson et al., 2013).

	Allocation factors	**Conversion factors**
Cereals (%)	0.2	0.77
Roots (%)	0.78	0.82
Sweets (%)	1	1
Vegetable oils (%)	0.2	1
Vegetables (%)	0.81	0.78
Fruits (%)	0.83	0.78
Pulses (%)	0.5	0.78
Meat (%)	1	0.66
Fish and seafood (%)	1	0.5
Dairy products (%)	1	1
Eggs (%)	1	0.85

Table A1.12 FLW percentages for each food category as a percentage of what enters on each supply chain stage. Unless stated otherwise, percentages are obtained from Section 2.1 and Gustavsson et al. (2013) for Europe region.

	Agricultural production	Postharvest handling & storage	Processing & packaging		Distribution		Consumption	
		*	Milling	Proc.	Fresh	Proc.	Fresh	Proc.
Cereals (%)	6.6	0.5	1.8	12.1	2.0	2.0	25.0	25.0
Roots (%)	8.3	4.9		14.7	7.0	3.0	17.0	12.0
Sweets (%)	6.6	0.0		2.0	10.0	2.0	19.0	15.0
Vegetable oils (%)	5.9	0.0		5.0	1.0	1.0	4.0	4.0
Vegetables (%)	8.3	9.0		2.0	10.0	2.0	19.0	15.0
Fruits (%)	6.5	10.8		2.0	10.0	2.0	19.0	15.0
Pulses (%)	6.6	8.2		5.0	10.0	2.0	19.0	15.0
Meat (%)	3.2	0.0		6.3	4.0	4.0	11.0	11.0
Fish and seafood (%)	9.4	0.0		6.0	9.0	5.0	11.0	10.0
Dairy products (%)	3.5	0.0		0.2	0.5	0.5	7.0	7.0
Eggs (%)	4.0	2.0		0.5	2.0	2.0	8.0	8.0

**Postharvest handling and storage losses percentages. This stage was not differentiated in the energy balance of this work. Therefore, these factors were applied in addition to agricultural production factors.*

This empirical index $EROI_{ce}$ is applied only to the four categories that stood out for high values of PED, FEL and EEL: fish and seafood, cereals, vegetables and meat. For its calculation, the kg of FLW of each category were found through the material flow analysis and multiplied by i) a specific factor for energy requirements for the management of each food category on each scenario and by ii) a specific factor of energy recovery for each food category (Table A1.13) The recovered primary energy was multiplied first by the conversion factor applied in this study to obtain the kg produced, and finally this data were multiplied by the Bedca Database factors (2018) to obtain the kilojoules of nutritional energy reintroduced in the FSC. This data were divided between the energy requirements, thus obtaining the dimensionless indicator allowing to compare the scenarios of each category.

Table A1.13 Results of the Energy return on investment – Circular economy index ($EROI_{ce}$) on fish and seafood, cereals, vegetables and meat, on each of the considered scenarios.

	Fish and seafood			Cereals			Vegetables			Meat		
	L	**I**	**AD**	**L**	**I**	**AD**	**L**	**I**	**AD**	**L**	**I**	**AD**
Energy recovered (MJ/kg)	0.3	4.4	11.7	0.2	6.5	9.4	0.2	3.1	2.7	0.3	5.1	11.9
Energy needed (MJ/kg)	0.6	1.2	1.3	0.6	1.2	1.3	0.6	1.2	1.3	0.6	1.2	1.3
Food loss (ktones)		381.2			2,682.1			3,257.8			1,371.5	
$EROI_{ce}$	**0.03**	**0.2**	**0.4**	**1.0**	**22.2**	**28.1**	**0.03**	**0.3**	**0.3**	**0.2**	**1.2**	**2.5**

All quantifications of Section 2.3 are subjected to some degree of uncertainty, and many assumptions have been done due to the unavailability of data. In order to make consistent estimations, some estimations from other similar studies are used: Vittuari et al. (2016), Infante-Amate et al. (2014), and Cuellar and Webber (2010). For other estimations, indirect calculation methods have been developed. It has been noticed the fact, that some of the mass-to-energy factors vary between studies, which is mainly due to the differences in the concrete system boundaries of each study or the age of the study. In the agricultural stage, it is assumed that differences in climates and soils as well as cultivation methods influence the resource use, but it has not been considered due to lack of data. According to Carlsson-Kanyama et al. (2003), most fruits are produced from plants with a long lifetime (trees) and usually these crops have to be maintained and cared during several years before production on-set. Resource inputs during those unproductive years should, ideally, be allocated to the production period of the tree. However, data about resource inputs during establishment were not found. It is imperative that more data on resource use during crop production becomes available to better understand the magnitude of uncertainties by estimating the resource use. Food which is cultivated in greenhouses, sometimes requires the use of heaters for their production. In the Spanish context, due to the favorable climatic conditions, the use of heaters is very low and it was decided to reject it. Data about energy used in the extraction, desalination and purification of water, especially in areas of intensive agriculture such as the region of Almeria, should be collected in the future. It is assumed that the energy intensity of the agricultural production of each food category is the same in Spain and in the importing countries, although this may not be correct, especially for importation from countries without mechanized agriculture. Data about energy use for food processing show large variations in terms of energy used for different products. Assumptions about transportation distances were done. For the PED calculation, it has been only taken into account imported products and omitted exportation, to avoid duplication of data. It is assumed that operations in retailers is similar than in wholesalers, in terms of storage temperature and applied cooling technology. Moreover, I Canals et al. (2007) proposed to consider the travelled distance by workers (especially for seasonal works) to farms. This factor was not considered as no information has been found. Finally, another important source of uncertainty in this work is due to the loss percentages used for the calculations. Data used from Gustavsson et al. (2013) are for Europe region and differences among countries are not considered. They are the best currently available data and have been assumed to be generalizable and extrapolated. Nonetheless, although they are considered a good reference for this work, they may lead to errors if they are assumed for a specific country. For this reason, they have been updated with Spanish data when possible based on the work developed in Section 2.2.

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A1. Supplementary material of Chapter 2

Contents:

Table A2.1 FLW generation at each region (in tons), divided in the 11 food categories and four stages considered. Stages: 1: agricultural production, 2: processing and packaging, 3: distribution, and 4: consumption. Regions: AN: Andalusia; AR: Aragon; AS: Principality of Asturias; BA: Balearic Islands; CN: Canary Islands; CT: Cantabria; CM: Castile-La Mancha; CL: Castile and Leon; CAT: Catalonia; EX: Extremadura; GA: Galicia; LR: La Rioja; MA: Community of Madrid; MU: Region of Murcia; NA: Chartered Community of Navarra; PV: Basque Country; VA: Valencian Community.

Spanish Region	Stage	Cereals	Roots and tubers	Sweets	Vegetable oils	Vegetables	Fruits	Pulses	Meat	Fish and seafood	Dairy products	Eggs
AN	1	258.6	55.1	5.1	21.8	362.0	360.4	10.2	20.6	13.5	33.0	7.4
	2	127.5	36.4	5.5	13.8	10.8	9.8	1.7	52.5	10.5	1.8	1.3
	3	21.1	16.0	7.0	3.2	59.1	48.6	3.8	39.6	11.1	5.8	6.3
	4	257.8	49.4	51.0	13.2	176.9	152.0	10.8	104.7	20.5	79.4	24.3
AR	1	140.9	30.0	1.4	11.9	197.2	196.4	5.6	27.1	0.2	24.0	14.2
	2	34.1	9.7	1.5	3.7	2.9	2.6	0.5	14.1	2.8	0.5	0.3
	3	3.3	2.5	1.1	0.5	9.3	7.6	0.6	6.2	1.8	0.9	1.0
	4	40.4	7.7	8.0	2.1	27.8	23.9	1.7	16.4	3.2	12.5	3.8
AS	1	2.2	2.3	0.0	0.0	24.2	28.4	0.9	0.0	0.0	0.0	0.2
	2	15.3	4.4	0.7	1.6	1.3	1.2	0.2	6.3	1.3	0.2	0.2
	3	2.6	2.0	0.9	0.4	7.4	6.1	0.5	5.0	1.4	0.7	0.8
	4	32.3	6.2	6.4	1.6	22.1	19.0	1.4	13.1	2.6	10.0	3.0
BA	1	14.7	3.1	0.2	1.2	20.6	20.5	0.6	1.7	2.9	3.4	0.6

Table A2.1 (Cont.) FLW generation at each region (in tons), divided in the 11 food categories and four stages considered. Stages: 1: agricultural production, 2: processing and packaging, 3: distribution, and 4: consumption. Regions: AN: Andalusia; AR: Aragon; AS: Principality of Asturias; BA: Balearic Islands; CN: Canary Islands; CT: Cantabria; CM: Castile-La Mancha; CL: Castile and Leon; CAT: Catalonia; EX: Extremadura; GA: Galicia; LR: La Rioja; MA: Community of Madrid; MU: Region of Murcia; NA: Chartered Community of Navarra; PV: Basque Country; VA: Valencian Community.

	2	4.5	1.3	0.2	0.5	0.4	0.3	0.1	1.9	0.4	0.1	0.0
	3	2.8	2.1	1.0	0.4	7.8	6.4	0.5	5.2	1.5	0.8	0.8
	4	33.9	6.5	6.7	1.7	23.3	20.0	1.4	13.8	2.7	10.4	3.2
CN	1	22.0	4.7	0.4	1.9	30.8	30.6	0.9	0.6	6.5	1.0	3.7
	2	10.8	3.1	0.5	1.2	0.9	0.8	0.1	4.4	0.9	0.2	0.1
	3	5.3	4.0	1.8	0.8	14.8	12.2	0.9	9.9	2.8	1.4	1.6
	4	64.5	12.4	12.7	3.3	44.2	38.0	2.7	26.2	5.1	19.9	6.1
CT	1	15.7	3.3	0.4	1.3	22.0	21.9	0.6	3.3	1.2	7.2	0.2
	2	10.8	3.1	0.5	1.2	0.9	0.8	0.1	4.4	0.9	0.2	0.1
	3	1.5	1.1	0.5	0.2	4.1	3.4	0.3	2.8	0.8	0.4	0.4
	4	18.0	3.4	3.6	0.9	12.3	10.6	0.8	7.3	1.4	5.5	1.7
CM	1	234.6	50.0	2.5	19.8	328.4	327.0	9.3	18.2	4.2	32.0	34.3
	2	62.0	17.7	2.7	6.7	5.2	4.8	0.8	25.5	5.1	0.9	0.6
	3	5.2	3.9	1.7	0.8	14.5	11.9	0.9	9.7	2.7	1.4	1.5
	4	63.2	12.1	12.5	3.2	43.4	37.3	2.6	25.7	5.0	19.5	6.0
CL	1	278.2	59.2	3.6	23.5	389.4	387.7	11.0	35.8	0.6	59.8	23.2

Table A2.1 (Cont.) FLW generation at each region (in tons), divided in the 11 food categories and four stages considered. Stages: 1: agricultural production, 2: processing and packaging, 3: distribution, and 4: consumption. Regions: AN: Andalusia; AR: Aragon; AS: Principality of Asturias; BA: Balearic Islands; CN: Canary Islands; CT: Cantabria; CM: Castile-La Mancha; CL: Castile and Leon; CAT: Catalonia; EX: Extremadura; GA: Galicia; LR: La Rioja; MA: Community of Madrid; MU: Region of Murcia; NA: Chartered Community of Navarra; PV: Basque Country; VA: Valencian Community.

	2	89.8	25.6	3.9	9.7	7.6	6.9	1.2	37.0	7.4	1.3	0.9
	3	6.2	4.7	2.1	1.0	17.4	14.3	1.1	11.7	3.4	1.7	1.9
	4	75.9	14.5	15.0	3.9	52.1	44.7	3.2	30.8	6.0	23.4	7.2
CAT	1	94.8	20.2	8.2	8.0	132.7	132.1	3.7	26.8	9.8	19.3	10.7
	2	204.7	58.4	8.9	22.1	17.3	15.7	2.7	84.4	16.9	3.0	2.1
	3	18.8	14.3	6.3	2.9	52.8	43.5	3.4	35.4	10.0	5.2	5.6
	4	230.4	44.1	45.6	11.8	158.1	135.9	9.7	93.6	18.4	71.0	21.7
EX	1	122.9	26.2	0.9	10.4	172.1	171.3	4.9	26.4	0.4	50.9	3.6
	2	20.7	5.9	0.9	2.2	1.7	1.6	0.3	8.5	1.7	0.3	0.2
	3	2.7	2.1	6.6	0.4	7.7	6.3	0.5	5.2	1.5	0.8	0.8
	4	33.5	6.4	2.8	1.7	23.0	19.8	1.4	13.6	2.7	10.3	3.2
GA	1	87.3	18.6	2.8	7.4	122.2	121.7	3.4	13.5	83.7	24.2	6.8
	2	69.1	19.7	3.0	7.5	5.9	5.3	0.9	28.5	5.7	1.0	0.7
	3	6.9	5.2	2.3	1.1	19.2	15.8	1.2	12.9	3.6	1.9	2.1
	4	83.9	16.1	16.6	4.3	57.5	49.5	3.5	34.0	6.7	25.8	7.9
LR	1	14.9	3.2	0.6	1.3	30.8	28.4	0.8	4.7	0.1	7.5	2.3

Table A2.1 (Cont.) FLW generation at each region (in tons), divided in the 11 food categories and four stages considered. Stages: 1: agricultural production, 2: processing and packaging, 3: distribution, and 4: consumption. Regions: AN: Andalusia; AR: Aragon; AS: Principality of Asturias; BA: Balearic Islands; CN: Canary Islands; CT: Cantabria; CM: Castile-La Mancha; CL: Castile and Leon; CAT: Catalonia; EX: Extremadura; GA: Galicia; LR: La Rioja; MA: Community of Madrid; MU: Region of Murcia; NA: Chartered Community of Navarra; PV: Basque Country; VA: Valencian Community.

	2	15.3	4.4	0.7	1.6	1.3	1.2	0.2	6.2	1.3	0.2	0.2
	3	1.6	1.2	0.5	0.2	4.5	3.7	0.3	3.0	0.9	0.4	0.5
	4	1.6	1.2	0.5	0.2	4.5	3.7	0.3	3.0	0.9	0.4	0.5
MA	1	23.7	5.0	1.7	2.0	33.2	33.0	0.9	1.5	0.2	3.1	2.0
	2	43.1	12.3	1.9	4.7	3.6	3.3	0.6	17.8	3.6	0.6	0.4
	3	16.2	12.3	5.4	2.5	45.3	37.3	2.9	30.4	8.6	4.4	4.8
	4	197.6	37.8	39.1	10.1	135.6	116.5	8.3	80.2	15.7	60.9	18.6
MU	1	33.4	7.1	2.2	2.8	46.8	46.6	1.3	7.3	1.7	6.9	3.0
	2	54.8	15.6	2.4	5.9	4.6	4.2	0.7	22.6	4.5	0.8	0.5
	3	3.7	2.8	1.2	0.6	10.3	8.5	0.7	6.9	2.0	1.0	1.1
	4	45.0	8.6	8.9	2.3	30.9	26.6	1.9	18.3	3.6	13.9	4.2
NA	1	30.7	6.5	1.0	2.6	37.1	38.2	1.1	2.6	1.5	5.6	3.3
	2	26.0	7.4	1.1	2.8	2.2	2.0	0.3	10.7	2.1	0.4	0.3
	3	1.6	1.2	0.5	0.2	4.5	3.7	0.3	3.0	0.9	0.4	0.5
	4	19.7	12.9	1.9	0.1	1.8	0.0	0.0	0.0	0.0	0.0	0.0
PV	1	21.4	4.5	1.3	1.8	29.9	29.8	0.8	2.6	1.5	5.6	3.4

	2	32.3	9.2	1.4	3.5	2.7	2.5	0.4	13.3	2.7	0.5	0.3
	3	5.5	4.2	1.8	0.8	15.4	12.7	1.0	10.3	2.9	1.5	1.6
	4	67.2	12.9	13.3	3.4	46.1	39.6	2.8	27.3	5.4	20.7	6.3
VA	1	68.7	14.6	3.1	5.8	96.1	95.7	2.7	4.4	5.4	4.0	10.0
	2	77.2	22.0	3.4	8.3	6.5	5.9	1.0	31.8	6.4	1.1	0.8
	3	12.5	9.5	4.2	1.9	35.0	28.8	2.2	23.5	6.6	3.4	3.7
	4	152.9	29.3	30.2	7.8	104.9	90.2	6.4	62.1	12.2	47.1	14.4

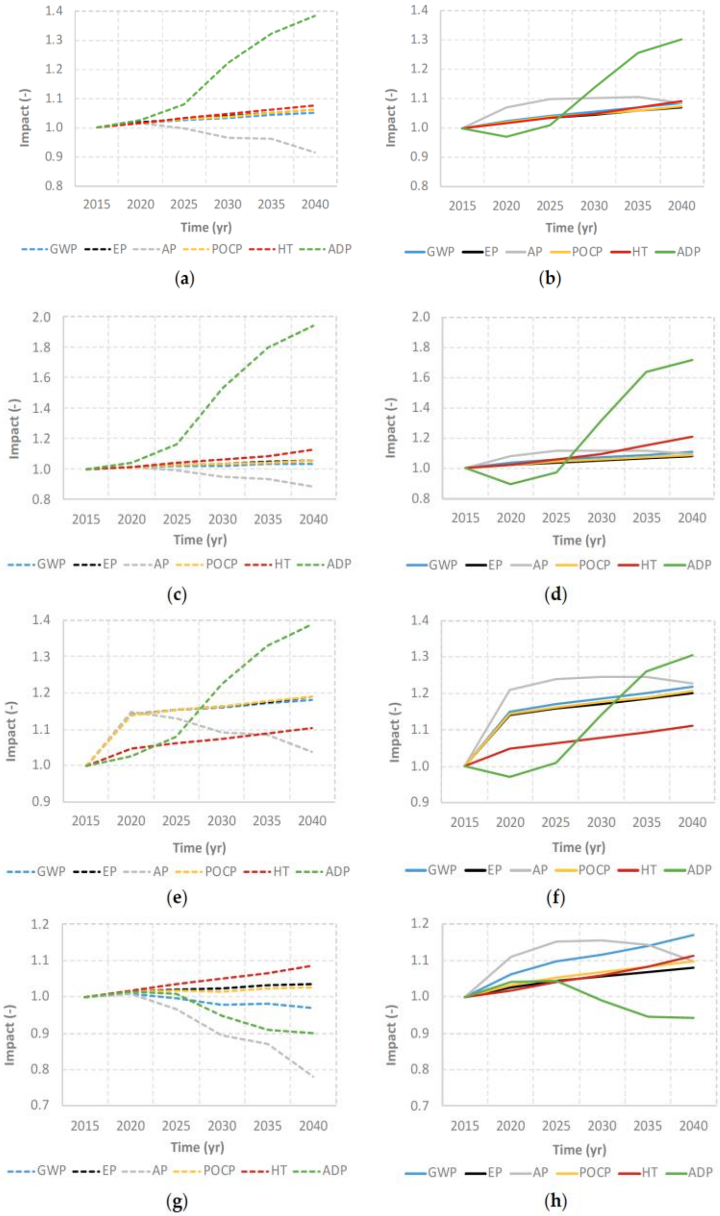

Figure A2.1 Environmental impacts of current FLW management. AN: (**a**) BAU, (**b**) 2DS; AR: (**c**) BAU, (**d**) 2DS; AS: (**e**) BAU, (**f**) 2DS; BA: (**g**) BAU, (**h**) 2DS; CN: (**i**) BAU, (**j**) 2DS; CM: (**k**) BAU, (**l**) 2DS; CL: (**m**) BAU, (**n**) 2DS; CAT: (**o**) BAU, (**p**) 2DS; GA: (**q**) BAU, (**r**) 2DS; LR: (**s**) BAU, (**t**) 2DS; MA: (**u**) BAU, (**v**) 2DS; MU: (**w**) BAU, (**x**) 2DS; PV: (**y**) BAU, (**z**) 2DS.

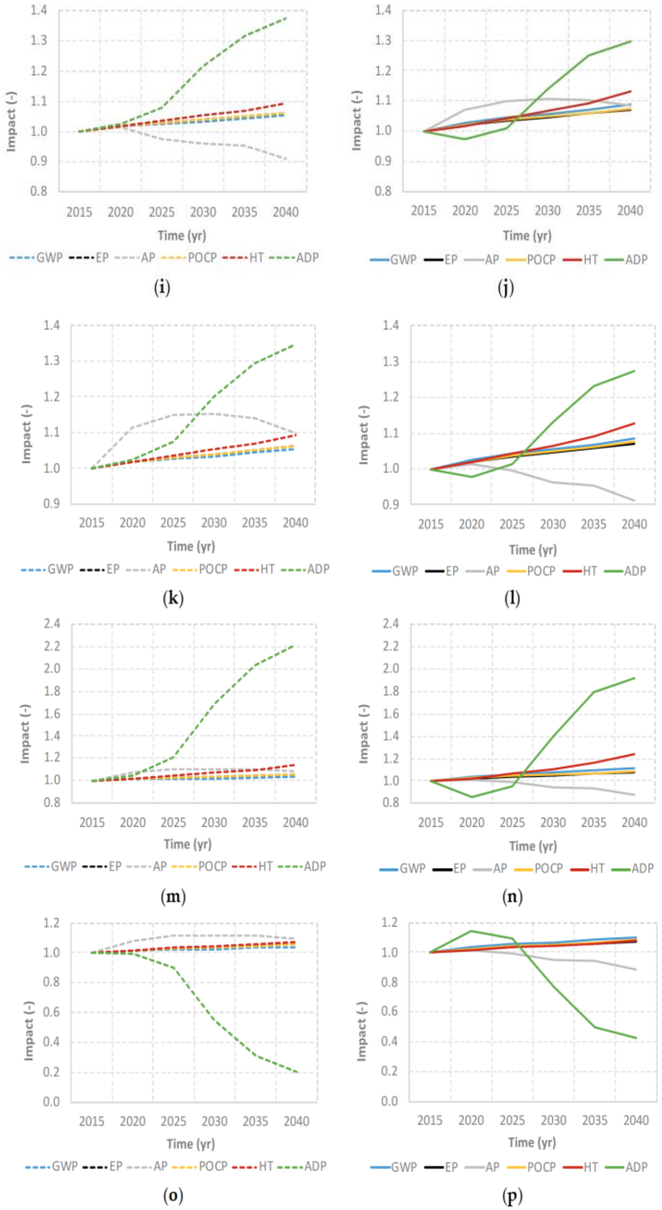

Figure A2.1 (Cont.) Environmental impacts of current FLW management. AN: (**a**) BAU, (**b**) 2DS; AR: (**c**) BAU, (**d**) 2DS; AS: (**e**) BAU, (**f**) 2DS; BA: (**g**) BAU, (**h**) 2DS; CN: (**i**) BAU, (**j**) 2DS; CM: (**k**) BAU, (**l**) 2DS; CL: (**m**) BAU, (**n**) 2DS; CAT: (**o**) BAU, (**p**) 2DS; GA: (**q**) BAU, (**r**) 2DS; LR: (**s**) BAU, (**t**) 2DS; MA: (**u**) BAU, (**v**) 2DS; MU: (**w**) BAU, (**x**) 2DS; PV: (**y**) BAU, (**z**) 2DS.

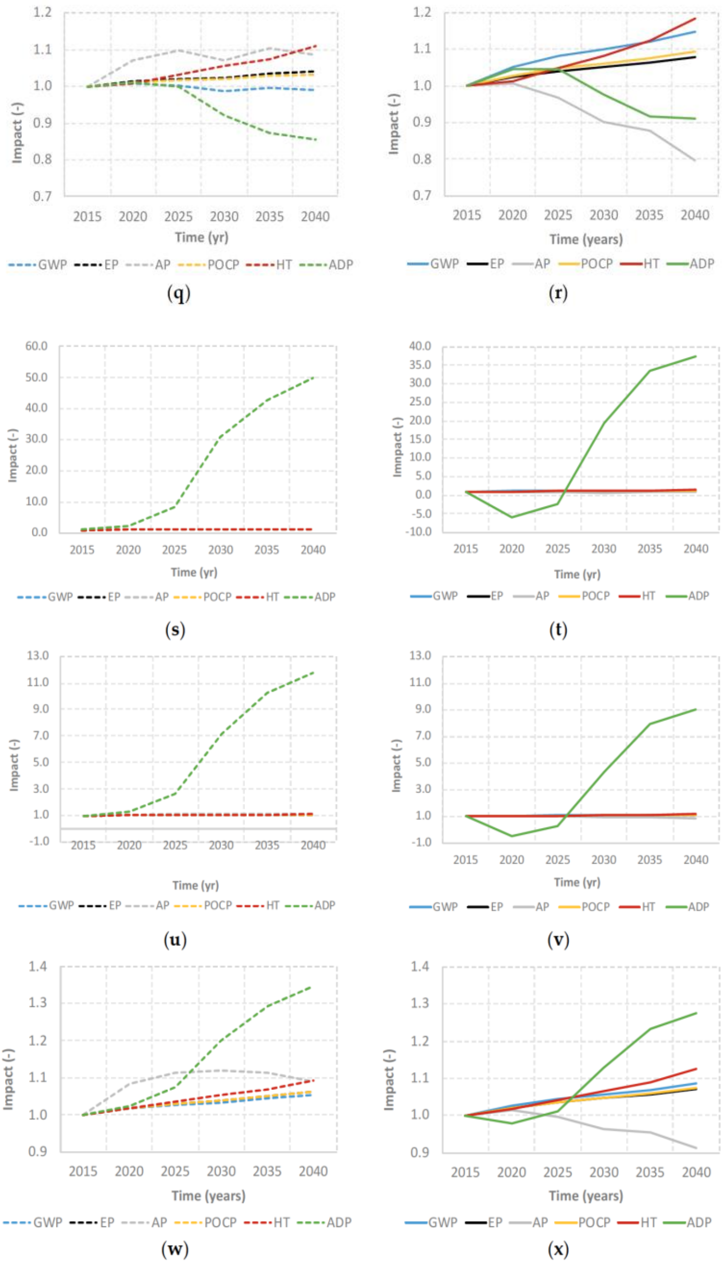

Figure A2.1 (Cont.) Environmental impacts of current FLW management. AN: (**a**) BAU, (**b**) 2DS; AR: (**c**) BAU, (**d**) 2DS; AS: (**e**) BAU, (**f**) 2DS; BA: (**g**) BAU, (**h**) 2DS; CN: (**i**) BAU, (**j**) 2DS; CM: (**k**) BAU, (**l**) 2DS; CL: (**m**) BAU, (**n**) 2DS; CAT: (**o**) BAU, (**p**) 2DS; GA: (**q**) BAU, (**r**) 2DS; LR: (**s**) BAU, (**t**) 2DS; MA: (**u**) BAU, (**v**) 2DS; MU: (**w**) BAU, (**x**) 2DS; PV: (**y**) BAU, (**z**) 2DS.

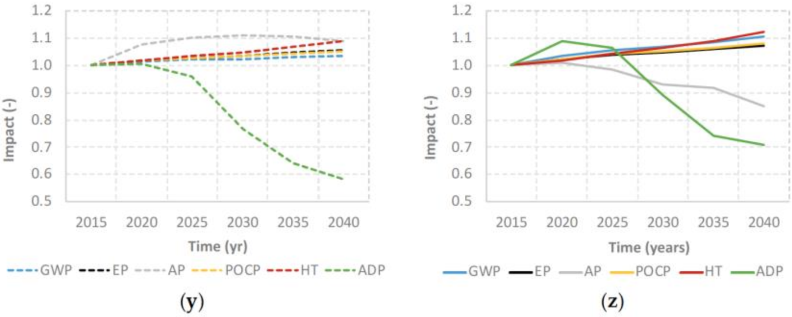

Figure A2.1 (Cont.) Environmental impacts of current FLW management. AN: (**a**) BAU, (**b**) 2DS; AR: (**c**) BAU, (**d**) 2DS; AS: (**e**) BAU, (**f**) 2DS; BA: (**g**) BAU, (**h**) 2DS; CN: (**i**) BAU, (**j**) 2DS; CM: (**k**) BAU, (**l**) 2DS; CL: (**m**) BAU, (**n**) 2DS; CAT: (**o**) BAU, (**p**) 2DS; GA: (**q**) BAU, (**r**) 2DS; LR: (**s**) BAU, (**t**) 2DS; MA: (**u**) BAU, (**v**) 2DS; MU: (**w**) BAU, (**x**) 2DS; PV: (**y**) BAU, (**z**) 2DS.

Table A2.2 Relative variation (%) of impacts as compared to the current scenario (S1) per region for the considered S2 management scenario.

Scenario	Region	Framework	GWP	EP	AP	POCP	HT	ADP
S2	AN	BAU	26.4	-65.6	-62.2	-76.4	-90.4	-97.2
		2DS	18.9	-66.1	-63.6	-76.6	-90.4	-97.2
	AR	BAU	15.0	-19.3	-20.2	-11.6	-51.0	-17.3
		2DS	10.8	-19.6	-21.0	-11.7	-51.0	-17.3
	AS	BAU	1.4	-6.7	-6.0	-9.9	-4.6	-12.1
		2DS	1.1	-6.7	-6.1	-9.9	-4.6	-12.1
	BA	BAU	1.6	-6.4	-5.8	-8.9	-5.5	-11.0
		2DS	1.2	-6.4	-5.9	-8.9	-5.5	-11.0
	CN	BAU	2.5	-11.8	-10.6	-17.4	-8.1	-21.3
		2DS	1.8	-11.8	-10.7	-17.4	-8.1	-21.3
	CT	BAU	1.8	-4.6	-4.4	0.0	-6.1	-7.0
		2DS	1.3	-4.7	-4.5	-5.6	-6.1	-7.0
	CM	BAU	24.6	-31.6	-33.0	-18.9	-83.3	-28.3
		2DS	17.6	-32.1	-34.3	-19.2	-83.4	-28.3
	CL	BAU	29.4	-39.0	-40.5	-24.6	-100.0	-36.2
		2DS	21.1	-39.5	-42.0	-24.9	-100.0	-36.2
	CAT	BAU	10.6	-55.1	-49.4	-81.8	-36.8	-100.0
		2DS	7.5	-55.3	-50.0	-81.9	-36.9	-100.0
	EX	BAU	13.8	-16.4	-17.4	-8.4	-46.4	-13.2
		2DS	9.9	-16.6	-18.1	-8.6	-46.4	-13.2
	GA	BAU	11.3	-25.3	-24.3	-27.7	-38.7	-35.6
		2DS	8.1	-25.5	-24.9	-27.8	-38.7	-35.6
	LR	BAU	2.2	-5.0	-4.9	-5.6	-7.4	-7.1
		2DS	1.6	-5.0	-4.9	-5.6	-7.4	-7.1
	MA	BAU	2.4	-33.2	-28.7	-55.4	-8.5	-66.6
		2DS	1.7	-33.2	-28.8	-55.4	-8.5	-66.6
	MU	BAU	3.8	-12.9	-11.9	-17.5	-12.5	-21.7
		2DS	2.7	-13.0	-12.1	-17.5	-12.5	-21.7
	NA	BAU	3.1	-5.7	-5.6	-5.6	-10.3	-7.4
		2DS	2.2	-5.8	-5.8	-5.6	-10.3	-7.4
	PV	BAU	2.4	-13.6	-12.1	-20.7	-8.1	-25.2

Table A2.2 (Cont.) Relative variation (%) of impacts as compared to the current scenario (S1) per region for the considered S2 management scenario.

		2DS	1.7	-13.7	-12.3	-20.7	-8.1	-25.2
	VA	BAU	7.1	-32.6	-29.4	-47.2	-24.5	-57.9
		2DS	5.1	-32.7	-29.8	-47.2	-24.5	-57.9

Table A2.3 Relative variation (%) of impacts as compared to the current scenario (S1) per region for the considered S3 management scenario.

Scenario	Region	Framework	GWP	EP	AP	POCP	HT	ADP
S3	AN	BAU	19.2	-61.9	-71.4	-80.7	-24.0	-97.2
		2DS	-3.2	-63.4	-75.5	-81.6	-24.1	-97.2
	AR	BAU	11.0	-17.3	-25.4	-14.0	-13.5	-17.3
		2DS	-1.7	-18.1	-27.7	-14.5	-13.5	-17.3
	AS	BAU	1.1	-6.5	-6.5	-10.1	-1.2	-12.1
		2DS	0.0	-6.5	-6.7	-10.1	-1.2	-12.1
	BA	BAU	1.2	-6.2	-6.4	-9.2	-1.5	-11.0
		2DS	-0.2	-6.2	-6.6	-9.2	-1.5	-11.0
	CN	BAU	1.8	-11.4	-11.4	-17.8	-2.2	-21.3
		2DS	-0.2	-11.6	-11.8	-17.8	-2.2	-21.3
	CT	BAU	1.3	-4.4	-5.0	-5.9	-1.6	-7.0
		2DS	-0.2	-4.5	-5.3	-5.9	-1.6	-7.0
	CM	BAU	17.9	-28.3	-41.4	-23.0	-22.1	-28.3
		2DS	-2.8	-29.6	-45.3	-23.7	-22.1	-28.3
	CL	BAU	21.4	-35.0	-50.6	-29.4	-26.5	-36.2
		2DS	-3.4	-36.6	-55.2	-30.3	-26.5	-36.2
	CAT	BAU	7.6	-53.6	-53.1	-83.6	-9,9	-100.0
		2DS	-1.5	-54.2	-54.8	-83.9	-9,9	-100.0
	EX	BAU	10.1	-14.5	-22.1	-10.7	-12.3	-13.2
		2DS	-1.5	-15.3	-24.2	-11.1	-12.3	-13.2
	GA	BAU	8.2	-23.7	-28.2	-29.5	-10.3	-35.6
		2DS	-1.4	-24.3	-30.0	-29.9	-10.3	-35.6

Table A2.3 (Cont.) Relative variation (%) of impacts as compared to the current scenario (S1) per region for the considered S3 management scenario.

	LR	BAU	1.6	-4.7	-5.5	-5.9	-2.0	-7.1
		2DS	-0.2	-4.8	-5.9	-6.0	-2-0	-7.1
	MA	BAU	1.7	-32.8	-29.6	-55.8	-2.4	-66.6
		2DS	-0.4	-33.0	-30.0	-55.9	-2.4	-66.6
	MU	BAU	2.8	-12.4	-13.2	-18.1	-3.3	-21.7
		2DS	-0.3	-12.6	-13.7	-18.2	-3.4	-21.7
	NA	BAU	2.3	-5.3	-6.6	-6.1	-2.7	-7.4
		2DS	-0.3	-5.5	-7.1	-6.2	-2.7	-7.4
	PV	BAU	1.8	-13.3	-13.0	-21.1	-2.2	-25.2
		2DS	-0.2	-13.4	-13.3	-21.2	-2.2	-25.2
	VA	BAU	-0.1	-31.6	-31.9	-48.3	-6.6	-57.9
		2DS	-0.9	-32.0	-33.0	-48.6	-6.6	-57.9

Table A2.4 Relative variation (%) of impacts as compared to the current scenario (S1) per region for the considered S4 management scenario.

Scenario	Region	Framework	GWP	EP	AP	POCP	HT	ADP
S4	AN	BAU	-11.6	-95.7	-87.5	-97.6	-5.9	-97.2
		2DS	-77.2	-100.0	-100.0	-100.0	-6.0	-97.2
	AR	BAU	-6.4	-36.4	-34.5	-23.5	-3.3	-17.3
		2DS	-43.5	-38.8	-41.5	-24.9	-3.3	-17.3
	AS	BAU	-0.5	-8.2	-7.3	-10.9	-0.3	-12.1
		2DS	-3.8	-8.4	-7.9	-11.1	-0.3	-12.1
	BA	BAU	-0.7	-8.2	-7.3	-10.2	-0.4	-11.0
		2DS	-4.7	-8.5	-8.1	-10.4	-0.4	-11.0
	CN	BAU	-0.9	-14.5	-12.8	-19.3	-0.6	-21.3
		2DS	-6.8	-14.8	-14.0	-19.5	-0.6	-21.3
	CT	BAU	-0.7	-6.7	-6.1	-7.0	-0.4	-7.0
		2DS	-5.2	-7.0	-6.9	-7.2	-0.4	-7.0
	CM	BAU	-10.5	-59.4	-56.3	-38.5	-5.3	-28.2

Table A2.4 (Cont.) Relative variation (%) of impacts as compared to the current scenario (S1) per region for the considered S4 management scenario.

		2DS	-71.1	-63.4	-67.9	-40.7	-5.4	-28.2
	CL	BAU	-12.7	-72.4	-68.5	-48.1	-6.4	-36.1
		2DS	-85.5	-77-2	-82.3	-50.8	-6.5	-36.1
	CAT	BAU	-4.9	-67.4	-59.7	-90.4	-2.5	-100.0
		2DS	-31.5	-69.1	-65.7	-91.4	-2.6	-100.0
	EX	BAU	-5.8	-31.9	-30.4	-19.3	-2.9	-13.2
		2DS	-39.5	-34.1	-36.8	-20.6	-3.0	-13.2
	GA	BAU	-5.0	-38.2	-35.1	-36.7	-2.5	-35.6
		2DS	-33.1	-40.0	-40.4	-37.8	-2.6	-35.6
	LR	BAU	-0.9	-7.5	-6.9	-7.3	-0.5	-7.1
		2DS	-6.3	-7.8	-7.9	-7.5	-0.5	-7.1
	MA	BAU	-1.2	-36.0	-31.1	-57.4	-0.7	-66.6
		2DS	-7.2	-36.4	-32.2	-57.6	-0.7	-66.6
	MU	BAU	-1.5	-17.1	-15.4	-20.4	-0.8	-21.7
		2DS	-10.6	-17.7	-17.1	-20.7	-0.9	-21.7
	NA	BAU	-1.2	-9.1	-8.5	-8.0	-0.7	-7.4
		2DS	-8.7	-9.6	-9.9	-8.3	-0.7	-7.4
	PV	BAU	-1.0	-16.3	-14.4	-22.6	-0.6	-25.2
		2DS	-6.9	-9.1	-15.5	-22.8	-0.6	-25.2
	VA	BAU	-3.2	-9.6	-36.3	-52.9	-1.7	-57.9
		2DS	-20.9	-16.3	-39.6	-53.6	-1.7	-57.9

Table A2.5 Relative variation (%) of impacts as compared to the current scenario (S1) per region for the considered S5 management scenario.

Scenario	Region	Framework	GWP	EP	AP	POCP	HT	ADP
S5	AN	BAU	34.6	-70.2	-74.2	-83.2	-40.7	-97.2
		2DS	1.8	-72.4	-80.4	-84.4	-40.8	-97.2
	AR	BAU	19.7	-22.0	-26.9	-15.4	-22.9	-17.3
		2DS	1.1	-23.2	-30.4	-16.1	-23.0	-17.3

Table A2.5 (Cont.) Relative variation (%) of impacts as compared to the current scenario (S1) per region for the considered S5 management scenario.

AS	BAU	1.9	-6.9	-6.6	-10.2	-2.1	-12.1
	2DS	0.2	-7.0	-6.9	-10.3	-2.1	-12.1
BA	BAU	2.1	-6.7	-6.5	-9.3	-2.5	-11.0
	2DS	0.1	-6.8	-6.9	-9.4	-2.5	-11.0
CN	BAU	3.2	-12.2	-11.6	-18.0	-3.7	-21.3
	2DS	0.3	-12.4	-12.2	-18.1	-3.7	-21.3
CT	BAU	2.4	-5.0	-5.2	-6.0	-2.7	-7.0
	2DS	0.2	-5.1	-5.6	-6.1	-2.7	-7.0
CM	BAU	32.1	-35.9	-44.0	-25.2	-37.5	-28.3
	2DS	1.8	-37.9	-49.7	-26.3	-37.5	-28.3
CL	BAU	38.4	-44.2	-53.7	-32.1	-45.0	-36.2
	2DS	2.1	-46.5	-60.5	-33.5	-45.0	-36.2
CAT	BAU	13.9	-57.0	-54.2	-84.6	-16.7	-100.0
	2DS	0.6	-57.9	-56.8	-85.1	-16.7	-100.0
EX	BAU	18.0	-18.8	-23.5	-11.9	-20.8	-13.2
	2DS	1.1	-19.9	-26.7	-12.6	-20.9	-13.2
GA	BAU	14.8	-27.2	-29.4	-30.6	-17.4	-35.6
	2DS	0.8	-28.2	-32.0	-31.1	-17.5	-35.6
LR	BAU	2.8	-5.4	-5.8	-6.1	-3.3	-7.1
	2DS	0.2	-5.5	-6.3	-6.2	-3.4	-7.1
MA	BAU	3.0	-33.6	-29.8	-56.0	-3.9	-66.6
	2DS	0.1	-33.8	-30.4	-56.2	-3.9	-66.6
MU	BAU	4.9	-13.6	-13.6	-18.4	-5.7	-21.7
	2DS	0.4	-13.9	-14.4	-18.6	-5.7	-21.7
NA	BAU	4.0	-6.2	-7.0	-6.4	-4.6	-7.4
	2DS	0.3	-6.5	-7.7	-6.5	-4.6	-7.4
PV	BAU	3.1	-14.0	-13.2	-21.3	-3.7	-25.2
	2DS	0.2	-14.2	-13.8	-21.4	-3.7	-25.2
VA	BAU	9.3	-33.8	-32.7	-49.0	-11.1	-57.9
	2DS	0.5	-34.4	-34.3	-49.3	-11.1	-57.9

Table A2.6 Relative variation (%) of impacts as compared to the current scenario (S1) per region for the considered S6 management scenario.

Scenario	Region	Framework	GWP	EP	AP	POCP	HT	ADP
S6	AN	BAU	45.1	-58.6	-66.3	-76.2	-60.1	-97.2
		2DS	31.5	-59.5	-68.8	-76.7	-60.1	-97.2
	AR	BAU	25.6	-15.4	-22.5	-11.4	-33.9	-17.3
		2DS	18.0	-15.9	-23.9	-11.7	-33.9	-17.3
	AS	BAU	2.4	-6.3	-6.2	-9.9	-3.1	-12.1
		2DS	1.7	-6.3	-6.3	-9.9	-3.1	-12.1
	BA	BAU	2.7	-5.9	-6.1	-8.9	-3.7	-11.0
		2DS	1.9	-6.0	-6.2	-8.9	-3.7	-11.0
	CN	BAU	4.1	-11.1	-10.9	-17.4	-5.4	-21.3
		2DS	2.9	-11.2	-11.2	-17.4	-5.4	-21.3
	CT	BAU	3.1	-4.2	-4.7	-5.5	-4.1	-7.0
		2DS	2.2	-4.2	-4.8	-5.6	-4.1	-7.0
	CM	BAU	41.8	-25.2	-36.7	-18.7	-55.4	-28.3
		2DS	29.3	-26.0	-39.0	-19.2	-55.4	-28.3
	CL	BAU	50.1	-31.3	-45.0	-24.3	-66.4	-36.2
		2DS	35.1	-32.2	-47.7	-24.9	-66.5	-36.2
	CAT	BAU	18.1	-52.3	-51.0	-81.7	-24.5	-100.0
		2DS	12.7	-52.6	-52.1	-81.9	-24.6	-100.0
	EX	BAU	23.4	-12.8	-19.4	-8.3	-30.8	-13.2
		2DS	16.4	-13.3	-20.7	-8.6	-30.8	-13.2
	GA	BAU	19.3	-22.3	-26.0	-27.6	-25.7	-35.6
		2DS	13.5	-22.6	-27.1	-27.8	-25.7	-35.6
	LR	BAU	3.7	-4.4	-5.1	-5.5	-4.9	-7.1
		2DS	2.6	-4.5	-5.3	-5.6	-4.9	-7.1
	MA	BAU	4.1	-32.5	-29.1	-55.4	-5.7	-66.6
		2DS	2.8	-32.6	-29.3	-55.4	-5.7	-66.6
	MU	BAU	6.4	-12.0	-12.5	-17.4	-8.3	-21.7
		2DS	4.5	-12.1	-12.8	-17.5	-8.4	-21.7
	NA	BAU	5.2	-4.9	-6.1	-5.6	-6.8	-7.4
		2DS	3.7	-5.0	-6.4	-5.6	-6.8	-7.4
	PV	BAU	4.1	-13.0	-12.5	-20.7	-5.4	-25.2

Table A2.6 (Cont.) Relative variation (%) of impacts as compared to the current scenario (S1) per region for the considered S6 management scenario.

	2DS	2.9	-13.1	-12.7	-20.7	-5.4	-25.2
VA	BAU	-0.2	-30.7	-30.5	-47.1	-16.3	-57.9
	2DS	8.5	-30.9	-31.2	-47.2	-16.3	-57.9

A3. Supplementary material of Chapter 4

Contents:

I. Electricity mixes calculation.

Table A3.1 Percentage of each energy to the electricity grid mix in March and April 2019 and 2020**.**

	Pre-COVID		COVID-19				
Energy (%)	**March 2019**	**April 2019**	**W11**	**W12**	**W13**	**W14**	**W15**
Hydropower	10.46	9.92	15.29	15.29	15.29	16.59	17.10
Nuclear	25.88	23.81	25.43	25.43	25.43	25.18	25.08
Hard coal	4.74	4.38	2.33	2.33	2.33	2.12	2.04
Fuel oil	3.59	3.69	2.70	2.70	2.70	2.83	2.88
Natural gas	23.42	27.21	19.26	19.26	19.26	22.21	23.38
Wind	24.15	24.03	27.49	27.49	27.49	22.32	20.25
Solar photovoltaic	3.99	3.68	5.16	5.16	5.16	6.50	7.03
Solar thermal	2.34	1.98	1.16	1.16	1.16	1.16	1.16
WtE	1.04	0.98	0.87	0.87	0.87	0.87	0.87
Biomass	0.39	0.40	0.31	0.31	0.31	0.24	0.22

II. *Nutritional FLW calculation*

Table A3.2 Nutritional composition of each food product assessed.

Food products	Kcal/g	Protein total (g/g)	AGS (g/g)	Sugar (g/g)	Fiber (g/g)	Na (mg/g)	K (mg/g)	Ca (mg/g)	Mg (mg/g)	Fe (mg/g)	Vit A (mcg ER/g)	Vit E (mg ET/g)	Vit C (mg/g)
Eggs	1.499	0.127	0.029	0.005	0.000	1.330	1.250	0.556	0.116	0.020	2.067	0.016	0.000
Beef	1.929	0.196	0.057	0.000	0.000	0.700	3.200	0.090	0.190	0.025	0.000	0.003	0.000
Chicken	1.128	0.217	0.009	0.000	0.000	0.600	3.200	0.121	0.230	0.010	0.000	0.002	0.046
Rabbit	1.128	0.217	0.009	0.000	0.000	0.600	3.200	0.121	0.230	0.010	0.000	0.002	0.046
Lamb	1.929	0.196	0.057	0.000	0.000	0.700	3.200	0.090	0.190	0.025	0.000	0.003	0.000
Pork	1.517	0.180	0.033	0.000	0.000	0.630	2.120	0.090	0.200	0.009	0.000	0.001	0.000
Processed meat	1.057	0.187	0.011	0.006	0.000	8.087	2.800	0.070	0.210	0.010	0.000	0.002	0.110
Hake	0.886	0.177	0.004	0.000	0.000	0.867	2.760	0.204	0.237	0.006	0.000	0.004	0.000
Pilchard	1.282	0.177	0.023	0.000	0.000	1.370	3.690	0.738	0.281	0.021	0.395	0.009	0.000
Tuna	1.348	0.247	0.010	0.000	0.000	0.390	3.300	0.080	0.230	0.013	0.260	0.009	0.000

Table A3.2 (Cont.) Nutritional composition of each food product assessed.

Atlantic mackerel	1.851	0.188	0.036	0.000	0.000	0.995	3.210	0.315	0.240	0.008	0.450	0.004	0.000
Salmon	1.748	0.200	0.019	0.000	0.000	0.470	3.740	0.200	0.265	0.006	0.130	0.019	0.000
Hake (frozen)	0.837	0.167	0.004	0.000	0.000	1.000	2.700	0.254	0.194	0.008	0.000	0.004	0.000
Mussels	0.734	0.108	0.007	0.000	0.000	2.900	3.240	0.630	0.335	0.084	0.840	0.007	0.000
Squid and octopus	0.707	0.140	0.004	0.000	0.000	1.365	3.163	0.203	0.317	0.039	0.150	0.012	0.000
Prawns and shrimps	0.883	0.180	0.003	0.000	0.000	3.050	2.210	1.150	0.690	0.033	0.000	0.015	0.000
Squid and octopus (frozen)	0.707	0.140	0.004	0.000	0.000	1.365	3.163	0.203	0.317	0.039	0.150	0.012	0.000
Prawns and shrimps (frozen)	0.737	0.165	0.001	0.000	0.000	3.800	0.750	1.300	0.470	0.026	0.020	0.029	0.000
Tuna (processed)	1.963	0.262	0.018	0.000	0.000	3.185	2.635	0.199	0.306	0.014	0.260	0.041	0.000

Table A3.2 (Cont.) Nutritional composition of each food product assessed.

Mussels (processed)	0.734	0.108	0.007	0.000	0.000	2.900	3.240	0.630	0.335	0.084	0.840	0.007	0.000
Anchovies (processed)	2.189	0.286	0.021	0.000	0.000	47.150	2.700	2.610	0.509	0.037	0.647	0.009	0.000
Milk	0.635	0.031	0.022	0.000	0.000	0.450	1.480	1.126	0.108	0.001	0.420	0.001	0.014
Shakes	0.570	3.740	0.017	0.045	0.000	0.854	1.808	1.366	0.160	0.001	0.270	0.000	0.004
Ice cream	0.570	3.740	0.017	0.045	0.000	0.854	1.808	1.366	0.160	0.001	0.270	0.000	0.004
Yoghurt	0.570	3.740	0.017	0.045	0.000	0.854	1.808	1.366	0.160	0.001	0.270	0.000	0.004
Butter	7.529	0.007	0.509	0.002	0.000	0.224	0.135	0.150	0.020	0.002	7.913	0.020	0.000
Fresh cheese	1.985	0.124	0.095	0.025	0.000	2.720	1.210	3.381	0.162	0.005	1.942	0.006	0.000
Semi-hard cheese	3.887	0.288	0.189	0.000	0.000	6.700	1.000	7.650	0.360	0.006	3.400	0.006	0.000
Hard cheese	4.326	0.283	0.213	0.000	0.000	6.700	0.800	7.665	0.463	0.007	3.883	0.006	0.000
Bread	2.357	0.083	0.004	0.018	0.035	6.500	1.200	0.560	0.251	0.016	0.000	0.000	0.000
Rice	3.391	0.068	0.002	0.000	0.019	0.050	0.980	0.121	0.330	0.007	0.000	0.002	0.000
Pasta	3.466	0.125	0.002	0.026	0.050	0.050	2.360	0.240	0.550	0.018	0.000	0.000	0.000

Table A3.2 (Cont.) Nutritional composition of each food product assessed.

Biscuits	4.544	0.070	0.097	0.267	0.031	2.173	1.104	1.177	0.250	0.020	0.144	0.000	0.000
Cereals	3.160	0.115	0.003	0.021	0.090	0.040	3.500	0.370	1.200	0.035	0.000	0.015	0.000
Choco tablet	5.340	0.079	0.183	0.539	0.026	0.665	2.690	1.645	0.418	0.005	0.515	0.004	0.000
Sugar	4.000	0.000	0.000	1.000	0.000	0.000	0.020	0.010	0.000	0.001	0.000	0.000	0.000
Legumes	3.042	0.242	0.002	0.013	0.130	1.254	5.815	0.566	0.743	0.068	0.133	0.009	0.017
Olive oil	8.991	0.000	0.128	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.120	0.000
Sunflower oil	8.991	0.000	0.116	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.560	0.000
Margarine	5.439	0.003	0.153	0.005	0.000	1.000	0.190	0.150	0.030	0.000	6.550	0.070	0.000
Potatoes	0.714	0.022	0.000	0.009	0.017	0.145	5.250	0.111	0.205	0.007	0.000	0.001	0.193
Tomatoe	0.185	0.009	0.000	0.035	0.011	0.178	2.358	0.108	0.098	0.005	0.739	0.009	0.192
Lettuce	0.165	0.014	0.001	0.017	0.015	0.215	2.340	0.399	0.099	0.007	1.058	0.005	0.064
Champis	0.254	0.013	0.000	0.043	0.018	0.365	2.580	0.303	0.140	0.004	6.749	0.003	0.135
Others vegetables	0.254	0.013	0.000	0.043	0.018	0.365	2.580	0.303	0.140	0.004	6.749	0.003	0.135

Table A3.2 (Cont.) Nutritional composition of each food product assessed.

Citric	0.404	0.010	0.000	0.083	0.017	0.040	1.790	0.405	0.126	0.003	0.400	0.002	0.518
Banana	0.911	0.011	0.001	0.173	0.023	0.010	3.850	0.077	0.332	0.005	0.181	0.003	0.118
Apples	0.507	0.003	0.001	0.116	0.021	0.070	1.200	0.060	0.040	0.002	0.117	0.005	0.050
Strawberries	0.496	0.004	0.000	0.113	0.023	0.020	1.250	0.100	0.070	0.002	0.100	0.005	0.050
Olives	1.102	0.011	0.018	0.000	0.040	19.295	0.715	0.485	0.210	0.011	0.347	0.020	0.000
Nuts	6.388	0.130	0.047	0.042	0.075	0.184	5.015	1.942	2.365	0.034	0.047	0.250	0.010
Tomato products	0.770	0.015	0.008	0.025	0.018	5.400	3.630	0.178	0.148	0.010	1.463	0.008	0.143
Gazpacho	0.770	0.015	0.008	0.025	0.018	5.400	3.630	0.178	0.148	0.010	1.463	0.008	0.143
Fabada	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842
Ketchup	0.770	0.015	0.008	0.025	0.018	5.400	3.630	0.178	0.148	0.010	1.463	0.008	0.143
Wine	0.663	0.011	0.018	0.000	0.040	19.295	0.715	0.485	0.210	0.011	0.347	0.020	0.000
Beer	0.630	0.032	0.001	0.023	0.038	0.050	2.720	2.720	2.720	0.007	0.250	0.004	0.060

III. Economic FLW calculation

Table A3.3 Prices at origin, distribution and consumption level for the food products under study.

	MARCH-APRIL 2019			COVID-19		
Food products	**Origin (€/kg)**	**Distribution (€/kg)**	**Consumption (€/kg)**	**Origin (€/kg)**	**Distribution (€/kg)**	**Consumption (€/kg)**
Eggs	0.841	1.107	2.355	1.025	1.290	1.450
Beef	3.589	4.498	9.570	3.790	7.501	15.960
Chicken	1.622	2.033	4.325	0.965	1.382	2.940
Rabbit	2.454	3.076	6.545	1.895	2.656	5.650
Lamb	3.872	4.853	10.325	2.780	5.116	10.885
Pork	2.209	2.768	5.890	1.500	2.806	5.970
Processed meat	3.188	3.995	8.500	3.197	4.007	8.526
Hake	4.401	5.135	7.335	4.414	5.150	7.357
Pilchard	2.793	3.259	4.655	2.801	3.268	4.669
Tuna	6.444	7.518	10.740	6.463	7.541	10.772
Atlantic mackerel	2.298	2.681	3.830	2.305	2.689	3.841
Salmon	6.633	7.739	11.055	6.653	7.762	11.088
Hake (frozen)	4.272	4.984	7.120	4.285	4.999	7.141
Mussels	1.596	1.862	2.660	1.601	1.868	2.668
Squid and octopus	5.133	5.989	8.555	5.148	6.006	8.581
Prawns and shrimps	7.056	8.232	11.760	7.077	8.257	11.795
Squid and octopus (frozen)	6.981	8.145	11.635	7.002	8.169	11.670
Prawns and shrimps (frozen)	6.543	7.634	10.905	6.563	7.656	10.938
Tuna (processed)	4.902	5.719	8.170	4.917	5.736	8.195
Mussels (processed)	5.178	6.041	8.630	5.194	6.059	8.656
Anchovies (processed)	12.288	14.336	20.480	12.325	14.379	20.541
Milk	0.257	0.514	0.685	0.258	0.515	0.687
Shakes	0.482	0.964	1.285	0.483	0.967	1.289
Ice cream	1.358	2.715	3.620	1.362	2.723	3.631
Yoghurt	0.694	1.388	1.850	0.696	1.392	1.856
Butter	2.818	5.636	7.515	2.827	5.653	7.538
Fresh cheese	1.961	3.923	5.230	1.967	3.934	5.246
Semi-hard cheese	3.214	6.428	8.570	3.223	6.447	8.596
Hard cheese	3.660	7.320	9.760	3.671	7.342	9.789
Bread	0.485	0.485	2.425	0.486	0.486	2.432
Rice	0.334	0.334	1.670	0.335	0.335	1.675

Table A3.3 (Cont.) Prices at origin, distribution and consumption level for the food products under study.

Pasta	0.390	0.390	1.950	0.391	0.391	1.956
Biscuits	0.710	0.710	3.550	0.712	0.712	3.561
Cereals	0.791	0.791	3.955	0.793	0.793	3.967
Choco tablet	0.000	4.085	8.170	0.000	4.097	8.195
Sugar	0.000	0.458	0.915	0.000	0.459	0.918
Legumes	1.063	1.325	2.325	1.066	1.329	2.332
Olive oil	2.228	2.693	3.325	2.135	3.151	3.890
Sunflower oil	0.707	0.855	1.055	0.705	0.853	1.053
Margarine	2.161	2.612	3.225	2.156	2.607	3.219
Potatoes	0.263	0.350	0.875	0.262	0.349	0.873
Tomatoe	0.352	0.704	1.760	0.630	0.792	1.980
Lettuce	0.567	1.134	2.835	0.190	0.560	1.400
Champis	0.754	1.508	3.770	1.900	1.446	3.615
Others vegetables	0.400	0.800	2.000	0.510	0.752	1.880
Citric	0.208	0.522	0.885	0.320	1.106	1.875
Banana	0.374	0.938	1.590	0.710	1.410	2.390
Apples	0.335	0.841	1.425	0.370	1.230	2.085
Strawberries	0.551	1.384	2.345	0.925	1.525	2.585
Olives	1.990	2.406	2.970	1.185	3.981	4.915
Nuts	1.882	4.726	8.010	1.854	4.655	7.890
Tomato products	0.295	0.590	1.475	0.291	0.581	1.453
Gazpacho	0.813	1.626	4.065	0.801	1.602	4.004
Fabada	1.510	1.884	3.305	1.488	1.856	3.255
Ketchup	0.492	0.984	2.460	0.485	0.969	2.423
Wine	1.836	2.219	2.740	1.808	2.186	2.699
Beer	0.264	0.264	1.320	0.260	0.260	1.300

A4. Dissemination of results

Scientific publications included in this Thesis

1. García-Herrero I, Hoehn D, Margallo M, Laso J, Bala A, Batlle-Bayer L, Fullana P, Vazquez-Rowe I, Gonzalez MJ, Durá MJ, Sarabia C, Abajas R, Amo-Setien FJ, 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.
2. 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, 767.
3. Aldaco R, Hoehn D, Laso J, Margallo M, Ruiz-Salmón I, Cristobal J, Kahhat R, Villanueva-Rey P, Bala A, Batlle-Bayer L, Fullana-i-Palmer P, Irabien A, Vázquez-Rowe I **(2020)** Food waste management during the COVID-19 outbreak: a holistic climate, economic and nutritional approach. *Sci. Total Environ.* 742, 140524.
4. Hoehn D, Laso J, Cristóbal J, Butnar I, Borrion A, Bala A, Fullana-i-Palmer P, Vázquez-Rowe I, Aldaco R, Margallo M **(2020)** Regionalized Strategies for Food Loss Management in Spain under a Life Cycle Thinking Approach. *Sustainability* 9(12), 1765.
5. Hoehn D, Margallo M, Laso J, Ruiz-Salmón I, Batlle-Bayer L, Bala A, Fullana-i-Palmer P, Aldaco R **(2021)** A novel composite index for the development of decentralized food production, food loss, and waste management policies: a Water-Climate-Food Nexus Approach. *Sustainability* 13, 2839.
6. Hoehn D, Laso J, Margallo M, Ruiz-Salmón I, Quiñones A, Amo-Setién FJ, Vázquez-Rowe I, Bala A, Batlle-Bayer L, Fullana-i-Palmer P, Aldaco R **(2021)** Introducing a degrowth approach to the circular economy policies of food production and food loss and waste management: towards a circular bioeconomy. *Sustainability* 12.
7. Hoehn D, Margallo M, Laso J, Ruiz-Salmón I, Vázquez-Rowe I, Aldaco R, Quinteiro P **(2021)** Water footprint assessment for best-regionalized strategies for food loss and waste management in Spain (*in press*).

Other related scientific publications

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

2. Vázquez-Rowe I, Laso J, Margallo M, García-Herrero I, **Hoehn D**, Amo-Setién F, Bala A, Abajas R, Sarabia C, Durá MJ, Fullana-i-Palmer P, Aldaco R **(2019)** Food loss and waste metrics: a proposed nutritional cost footprint linking linear programming and life cycle assessment. *Int. J. Life Cycle Assess.* 25, 1197-1209.
3. Laso J, Campos C, Fernández-Rios A, **Hoehn D**, del Rio A, Ruiz-Salmón I, Cristóbal J, Quiñones A, Amo-Setién FJ, Ortego MC, Tezanos S, Abajas R, Bala A, Fullana-i-Palmer P, Puig R, Margallo M, Aldaco R, Abejón R **(2021).** *Sustainability* 13, 125.

Contributions to national and international congress

1. Laso J, **Hoehn D,** Ruiz-Salmón I, Margallo M, San Román MF, Irabien A, Aldaco R, Opportunities for the Cantabrian agro-food system under a Food-Energy-Water Nexus approach: the case study of organic tomatoes, LCA FOOD 2020, 13-16 October, 2020.
2. **Hoehn D**, Laso J, Margallo M, Quiñones A, Amo-Setién FJ, Aldaco R, Bala A, Batlle-Bayer L, Fullana-i-Palmer P, Vázquez-Rowe I. Introducing a Degrowth Approach to the Circular Economy Policies of Food Production and Food Loss Management: Towards a Spiral Bioeconomy. 15th Conference on Sustainable Development of Energy, Water and Environment Systems, SDEWES. Cologne, 1-5 September, 2020.
3. **Hoehn D**, Laso J, Margallo M, Ruiz-Salmon I, Aldaco R. A Novel Composite Index for the Development of Decentralized Food Production and Food Loss Management Policies: a Water-Energy-Food Nexus Approach. 15th Conference on Sustainable Development of Energy, Water and Environment Systems, SDEWES. Cologne, 1-5 September, 2020.
4. **Hoehn D**, Laso J, Margallo M, Butnar I, Solano-Rodriguez B, Aldaco R. An open question for the European bioenergy future: how should food waste energy be managed?. The 22nd Conference on Process Integration. Modelling, and Optimization for Energy Saving and Pollution Reduction, PRES'19. Agios Nikolaos, Creete, 20-23 October, 2019
5. Leivas R, Laso J, **Hoehn D**, Margallo M, Fullana-i-Palmer P, Aldaco R. Product vs corporate carbon footprint: a case study for the spirits drinks sector. The 22nd Conference on Process Integration. Modelling, and Optimisation for Energy Saving and Pollution Reduction, PRES'19. Agios Nikolaos, Creete, 20-23 October, 2019
6. **Hoehn D**, Laso J, Margallo M, Bala A, Fullana-i-Palmer P, Aldaco R. Environmental efficiency of the Spanish food packaging waste management system. 1st Mediterranean Symposium on Life Cycle Assessment (MeSyLCA 2019). Santander, 9-21 June, 2019.
7. Aldaco R, **Hoehn D**, Laso J, Margallo M, Butnar I, Solano-Rodríguez B. A consequential life cycle approach for the food waste energy management: assessing bioenergy generation on the electricity grid mix and related GHG emissions. CILCA Conference of the Iberoamerican Life Cycle Network (RICV). Cartago, Costa Rica, 15-19 Juli, 2019.
8. **Hoehn D**, García-Herrero I, Margallo M, Laso J, Bala A, Fullana-i-Palmer P, Vázquez-Rowe I, Dura MJ, Sarabia C, Abajas R, Quiñones A, Irabien A, Aldaco R, Irabien A. Assessment of food waste management based on the nexus food-energy-water-climate. 9º Congreso International de Química de la ANQUE. San Pedro del Pintar, Murcia, 17-20 June, 2018.