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Vanessa Sofia Melo Magalhães

Framework development for the prevention of food loss and waste: an analysis along the fresh food supply chain

Doctoral Thesis in Mechanical Engineering, specialisation in Advanced Production Systems, supervised by Professor Luís Miguel Domingues Fernandes Ferreira and Professor Cristóvão Silva and submitted to the Department of Mechanical Engineering, Faculty of Sciences and Technology of the University of Coimbra.

July 2021

Faculty of Sciences and Technology
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What we know is a drop, what we don't know is an ocean.

Isaac Newton

Acknowledgments

At the start of this journey I thought that I would work to uncover a "big truth" at the end of my PhD, a final answer that could potentially "unlock" the problem of food loss and waste and finally lead to its resolution. However, as time went by, even though some "answers" have been discovered within this thesis, I started to realise that I had even more questions than before and that I was nowhere near to understand the "whole thing". Today, after ending this journey, I strongly believe that there is still much more to understand and to investigate in future endeavours to expand the limits of the current understanding concerning food loss and waste.

Above all, this thesis would not have seen the light of day if not for the guidance and positive encouragement from my supervisors – Professor Luís Ferreira and Professor Cristóvão Silva. Their infinite patience, constant availability and the capacity to inspire in me a self-confidence and a desire to persevere, greatly contributed to the accomplishment of this thesis and instilled in me a philosophy of continuous improvement. To each I am immensely grateful.

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Abstract

The problem of food loss and waste along food supply chains has recently been in the spotlight, particularly since it was integrated in the United Nations' 2030 Agenda for Sustainable Development. The Member States made a commitment to reduce the global food loss and waste generated along food supply chains from production until consumption by 2030, to ensure sustainable consumption and production patterns in the future. This urgency in reducing food loss and waste can be explained by its many negative economic, environmental and social impacts, which are worrying researchers around the world, who are concerned about how we can feed an ever-increasing population without leading to the depletion of natural resources. However, despite the increasing research done on this issue, there are still several knowledge gaps that need to be addressed. The complexity of food loss and waste requires in-depth analyses, from a holistic perspective, to better understand its causes and to identify the most promising mitigation strategies, which are lacking from the literature. To fill these gaps, the main objectives of this thesis are: to contribute to the understanding of the phenomenon of food loss and waste along fresh food supply chains and provide a research framework to guide future investigations seeking to determine the most promising mitigation strategies.

To achieve these objectives, the thesis is divided into two parts, comprising five chapters. The aim of the first part (comprising chapter 1) is to provide a clear view of the literature on the problem of food loss and waste along food supply chains. Chapter 1 performs a systematic literature review of the causes and the mitigation strategies of food loss and waste, taking into account different stages of the food supply chain, countries with different levels of economic development, and different food products. This part of the thesis helps us to identify the main research opportunities in the field and to develop a research framework to guide future investigations seeking to identify the most promising strategies to mitigate food loss and waste along food supply chains. The objective of the second part (comprising chapters 2, 3 and 4) is to provide empirical evidence of the suitability and the validity of the framework developed in the first part. Focus group discussions were used, in Chapter 2, to analyse the causes of food loss and waste in the Portuguese fruit and vegetable supply chain, and in-depth interviews were conducted, in Chapter 3, to analyse the causes of food loss and waste in the Brazilian beef supply chain. The Interpretive Structural Modelling methodology was employed in both chapters to model the interrelationship between the causes and the Matrix Impact of Cross Multiplication Applied to Classification analysis allowed us to identify the root causes of food loss and waste for the scenarios under study. Chapter 4 also used focus group discussions to identify potential mitigation strategies to reduce food loss and waste along the Portuguese fruit and vegetable supply chain.

The fuzzy Step-Wise Weight Assessment Ratio Analysis was employed to determine the relative weights of the evaluation criteria to assess the performance of the mitigation strategies and the fuzzy Weighted Aggregated Sum Product Assessment methodology was employed to evaluate and rank the mitigation strategies, prioritising the ones with greater potential to reduce food loss and waste in the Portuguese fruit and vegetable supply chain.

Overall, the thesis contributes to the growing body of literature on food loss and waste, by going beyond the identification of its causes and the strategies to mitigate it. The thesis offers multidimensional and holistic methodologies, applied from a supply chain perspective, to analyse the interrelationships between the causes of food loss and waste and to evaluate and prioritise the mitigation strategies to reduce it along fresh food supply chains. Moreover, the findings are of significant interest to practitioners and managers, by providing a framework that can be replicated step-by-step to enable the reduction of food loss and waste within their businesses or supply chains. This thesis revealed that the root causes of food loss and waste in the two supply chains studied were related to logistics. In the Brazilian beef supply chain, the root causes also included causes related to demand and to the product. Furthermore, the thesis highlighted the role of information management in the Portuguese fruit and vegetable supply chain to improve the information flow along the supply chain and ensure that the decision-making process is supported by sufficient and real-time information, promoting the reduction of food loss and waste throughout the supply chain.

Keywords: Food loss and waste; Supply chain; Fresh food products; Root causes; Mitigation strategies; Multi-criteria decision-making.

Resumo

O problema da perda e do desperdício alimentar ao longo das cadeias de abastecimento alimentar tem estado recentemente no centro das atenções, tendo sido integrado na Agenda 2030 das Nações Unidas para o Desenvolvimento Sustentável. Os Estados-Membros comprometeram-se a reduzir a perda global de alimentos e os resíduos gerados ao longo das cadeias de abastecimento alimentar, desde a produção até ao consumo, até 2030, para garantir padrões de consumo e produção sustentáveis no futuro. Esta urgência em reduzir perdas e desperdícios alimentares pode ser explicada pelos impactos económicos, ambientais e sociais negativos, que inquietam os investigadores ao redor do mundo, em particular aqueles que se preocupam em alimentar uma população cada vez maior sem levar ao esgotamento dos recursos naturais. No entanto, apesar do aumento das investigações sobre este assunto, ainda existem várias lacunas de conhecimento que precisam ser abordadas. A complexidade da perda e do desperdício alimentar requer análises holísticas aprofundadas, para melhor compreender as causas e identificar as estratégias de mitigação mais promissoras. Para preencher estas lacunas, os principais objetivos da tese são: contribuir para a compreensão do fenómeno da perda e do desperdício alimentar ao longo das cadeias de abastecimento de alimentos frescos e fornecer um modelo conceptual para orientar futuras investigações que procurem determinar as estratégias de mitigação mais promissoras.

Para atingir estes objetivos, a tese foi dividida em duas partes e quatro capítulos. A primeira parte (composta pelo capítulo 1) visa fornecer uma visão clara da literatura sobre o problema em análise. O Capítulo 1 realiza uma revisão sistemática da literatura sobre as causas e as estratégias de mitigação da perda e do desperdício alimentar, tendo em consideração os diferentes estágios da cadeia de abastecimento alimentar, países com diferentes níveis de desenvolvimento económico e diferentes produtos alimentares. Esta parte da tese ajuda a identificar as principais oportunidades de investigação futura e a desenvolver um modelo conceptual para orientar futuras investigações que procurem identificar as estratégias mais promissoras para mitigar a perda e o desperdício alimentar ao longo das cadeias de abastecimento alimentar. A segunda parte (composta pelos capítulos 2, 3 e 4) visa fornecer provas empíricas da adequação e validade do modelo conceptual desenvolvido na primeira parte. As discussões do grupo focal foram usadas, no Capítulo 2, para analisar as causas da perda e do desperdício alimentar numa cadeia de abastecimento de frutas e vegetais em Portugal, e entrevistas em profundidade foram realizadas, no Capítulo 3, para analisar as causas numa cadeia de abastecimento de carne bovina no Brasil. A metodologia *Interpretive Structural Modelling* foi utilizada em ambos os capítulos para modelar a inter-relação entre as causas e a análise *Matrix Impact of Cross Multiplication Applied to Classification* permitiu identificar as causas-raiz para os cenários em estudo. O Capítulo 4 utilizou discussões de grupos focais para identificar estratégias de mitigação potenciais para a cadeia de abastecimento de frutas e vegetais em Portugal. A metodologia *fuzzy Step-Wise Weight Assessment Ratio Analysis* foi utilizada para determinar os pesos relativos dos critérios de avaliação do desempenho das estratégias de mitigação e a metodologia *fuzzy Weighted Aggregated Sum Product Assessment* foi utilizada para avaliar e classificar as estratégias de mitigação, priorizando aquelas com maior potencial de redução das perdas e do desperdício alimentar.

No geral, a tese contribui para o corpo de literatura sobre a perda e o desperdício alimentar, indo além da identificação das suas causas e estratégias de mitigação. A tese oferece metodologias multidimensionais e holísticas para analisar as inter-relações entre as causas e avaliar e priorizar as estratégias de mitigação. Além disso, as descobertas interessam a profissionais e gerentes, pois fornecem um modelo que pode ser replicado para alavancar a redução da perda e do desperdício alimentar nos seus negócios ou nas cadeias de abastecimento em que estão inseridos. Esta tese revelou que as causas raiz nas duas cadeias de abastecimento estudadas estão relacionadas com a logística. Na cadeia de abastecimento de carne bovina Brasileira, as causas raízes também estão relacionadas com a procura e as características do produto. Adicionalmente, a tese destaca o papel da gestão da informação na cadeia de abastecimento de frutas e vegetais Portuguesa para melhorar o fluxo de informação ao longo da cadeia e garantir que o processo de tomada de decisão é suportado por informação suficiente e em tempo real, promovendo a redução da perda e do desperdício alimentar.

Palavras-chave: Perda e desperdício alimentar; Cadeia de abastecimento; Produtos alimentares frescos; Causas-raiz; Estratégias de mitigação; Modelos multicritério.

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Acronyms

AHP – Analytical Hierarchy Process

ANP – Analytic Network Process

DEMATEL – DEcision MAking Trial and Evaluation Laboratory

ERP – Enterprise Resource Planning

FGD – Focus Group Discussion

FLW – Food Loss and Waste

FSC – Food Supply Chain

FVSC – Fruit and Vegetable Supply Chain

ISM – Interpretive Structural Modelling

KPI – Key Performance Indicator

MCDM – Multi-Criteria Decision Making

MICMAC – Matrix Impact of Cross Multiplication Applied to Classification

RFID – Radio-Frequency IDentification

SC – Supply Chain

SDG – Sustainable Development Goal

SWARA – Step-wise Weight Assessment Ratio Analysis

TISM – Total Interpretive Structural Modelling

TTI – Time Temperature Indicator

WASPAS – Weighted Aggregated Sum Product Assessment

WPM – Weighted Product Model

WSM – Weighted Sum Model

INTRODUCTION

Approximately 30% of the annual global food produced for human consumption is never consumed by human beings (Priefer et al., 2016), which in itself is a moral paradox, considering that nearly 690 million people around the world, approximately 9% of the global population, were undernourished in 2019 (Lipinski et al., 2013; FAO et al., 2020). This situation is even more reprehensible since estimates indicate that the food loss and waste (FLW) generated annually could potentially feed up to 4 times the number of hungry people around the world (Yetkin Özbük and Coşkun, 2020). This means that reducing FLW by 25% might be sufficient to provide the means to end human starvation.

Besides the concerns regarding populations' malnutrition, FLW also impacts negatively on food supply chains (FSCs) in the environmental, social and economic dimensions (Koester, 2014; Papargyropoulou et al., 2014; Aschemann-Witzel et al., 2015). FLW is associated with the inefficient use of water and land (FLW requires 173–250 km^3 of water consumption annually and occupies a cropland area of 198 million hectares every year), and produces unnecessary greenhouse gas emissions (without accounting for GHG emissions from land use change, the carbon footprint of FLW amounts to 3.3 Gtonnes of CO_2 equivalent, making it the third-highest emitter after the USA and China), influencing food security in the long run (Lipinski et al., 2013; FAO, 2013; HLPE, 2014; Koester, 2014; Vilariño et al., 2017). It further contributes to the reduction of the global and local availability of food and to increases in the price of food, leading to significant loses in revenue and reducing the economic well-being of all members of FSCs (Koester, 2014). The terms "food loss and waste" and "food wastage" will be used interchangeably in this thesis to address all food products (including the edible and the inedible parts of food) intended for human consumption that were discarded, for any reason, somewhere between primary production until the food product reached the supermarket shelves.

Krishna Bahadur et al. (2016) states that even though the efforts to feed the world population sustainably are focused on boosting crop yields and increasing farm productivity, there is a growing body of work that considers the reduction of FLW as an effective strategy to improve global food security and reduce the impact of agriculture on the planet's ecosystems. However, FLW is not a problem with an easy fix, particularly because the consumption of food is dictated by consumers that are increasingly more demanding regarding food quality, safety and diversity, and that are paying increasing attention to sustainability (Van der Vorst et al., 2009). Combining this with the limited shelf life of fresh products and the uncertainty concerning food demand, due to seasonality, variation in prices and other factors, these factors have led to the increasing complexity of FSCs (Van der Vorst et al., 2009). The main aim of this thesis is, therefore, to understand the phenomenon of FLW along fresh FSCs. The focus of this thesis is on the level of the supply chain and the household consumption is not considered since FLW at this stage is mostly related to consumers' attitudes (Schanes et al., 2018) and there is already an extensive body of knowledge examining the: psychological, social, situational, demographic and socioeconomic factors of FLW at this stage (e.g., Stancu et al., 2016; Abdelradi, 2018; Gao et al., 2021). Since these causes of FLW are mainly restricted to the generation of FLW at the end of FSCs, then this stage was intentionally excluded from the analysis performed in this thesis.

An FSC (Figure *I*) is defined as the "connected series of activities used to produce, process, distribute and consume food" (Vittuari et al., 2016) and it has the particularity of dealing with products that are perishable in nature. Contrary to what one may think, FLW is evident in all stages of FSCs and does not happen solely at the consumers' end. For instance, estimates show that the largest share of FLW in the European Union happens at the consumption level (representing 46% of the total FLW), but the majority of FLW is still generated at the earlier stages of FSCs, with the primary production stage, the processing and manufacturing stage, and the distribution and retail stage being responsible for 25%, 24% and 5% of the total FLW, respectively (Caldeira et al., 2019). Even though FLW occurs along FSCs, for all groups of food, it is generally highest for highly perishable food products, with 41% of fruits, 46% of vegetables and 23% of meat products ending up as FLW in the European Union, for example (Caldeira et al., 2019).

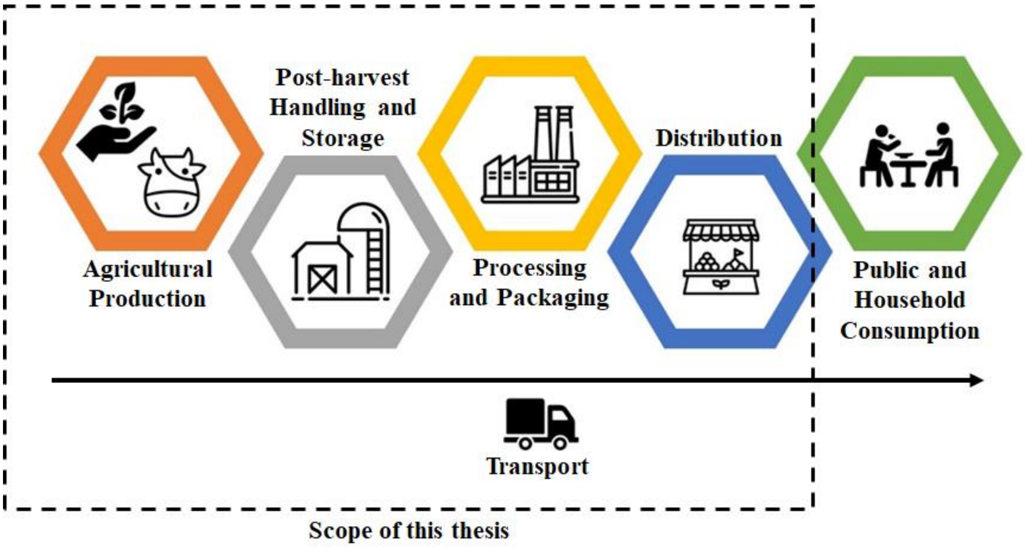

Figure I – Schematic representation of the food supply chain.

Before the food products reach the supermarket shelves, they are subjected to a mix of different processes, like transportation, processing, and packaging, which changes their original form and contributes to part of them being lost or wasted in the process, for a variety of different reasons (Martínez et al., 2014). Because of this, appropriate policies and methods for managing the products that are discarded from FSCs have been developed (Papargyropoulou et al., 2014). The first categorisation of the different options available to deal with FLW was the food waste hierarchy (illustrated in Figure II). According to this hierarchy, the different waste management options can be classified regarding the final destination of the wasted products and include, from the least to the most preferable option: disposal, recovery, recycle, reuse and prevention (Plazzotta et al., 2017).

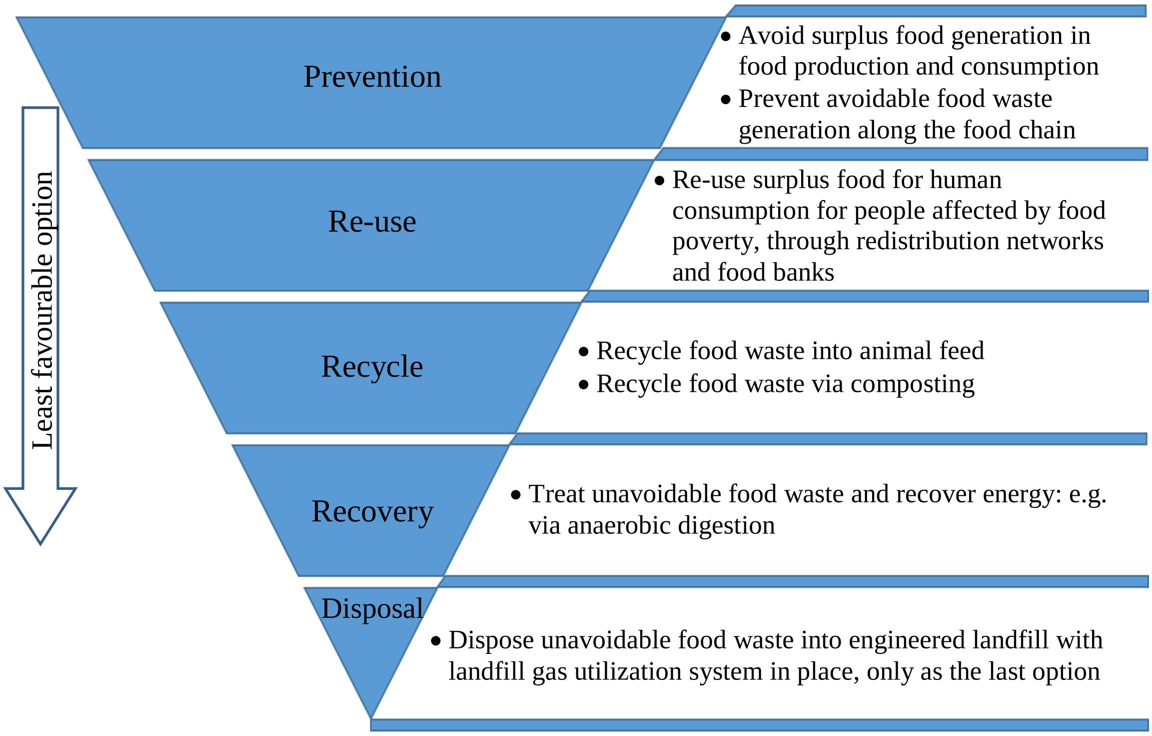

Figure II – The food waste hierarchy (source: Papargyropoulou et al., 2014).

The disposal of food not fit for human consumption is the least preferable option in the food waste hierarchy. FLW going to sewers, sent to landfills or incinerated without any form of energy recovery are the least viable waste management options and should be avoided at all costs. Incinerating FLW creates emissions that can impact human health and the environment negatively and landfilling also has negative impacts on the environment through the generation of methane gas, which has 25 times the global warming potential of CO_2, over a 100-year time horizon (Buzby and Hyman, 2012).

Energy recovery, also called waste-to-energy, refers to the recovery of the energy contained in the waste material and there are several strategies, including thermochemical conversions (incineration, pyrolysis and gasification) or biochemical strategies (anaerobic digestion and fermentation), to do so (Plazzotta et al., 2017). These strategies can be used, for example, to produce biofuel and bioenergy (Manzocco et al., 2016). The residues from biofuel production can further be used for heat, electricity, production of compressed or liquefied natural gas (Plazzotta et al., 2017) or even as a soil fertilizer (Manzocco et al., 2016). Therefore, energy recovery can potentially reduce the use of non-renewable resources and help decrease the impacts of global warming. However, there is an increasing concern about the emissions adversely affecting the environment and the high operative costs of such strategies (Manzocco et al., 2016).

Recycling encompasses strategies to recover FLW materials after performing a major modification of their characteristics (Manzocco et al., 2016). Even if processing is efficiently performed, a part of food products is inevitably lost, due to the presence of unusable and inedible parts and this unavoidable waste should be recycled, if possible, instead of being treated for energy recovery or sent to landfills. The goal can be to extract a specific compound or to recycle the whole mass of the wasted product (Plazzotta et al., 2017). One recycling strategy is to transform FLW into animal feed. This is the most used strategy for cereals and dairy discards. However, this option depends on the food's origins and relevant regulation, such as those hindering animal based feed for livestock (Manzocco et al., 2016). Another strategy is the aerobic composting of FLW, which is an eco-friendly method to produce fertilizer (Manzocco et al., 2016; Plazzotta et al., 2017). Processing into flour is another recycling option. Its main advantages are that valuable products such as adsorbents and functional flours are obtained from low-cost raw materials and no residual waste has to be disposed of. However, the main issue is the high cost for drying, due to the high water content of food products. Consequently, the production of FVW flour is affordable only if high value-added ingredients and products are developed (Plazzotta et al., 2017).

Reuse indicates the use of FLW materials for purposes other than the originally intended, with minor or without modification of their properties (Plazzotta et al., 2017). The main strategies for reuse include soil amendment and animal feed, but these strategies are difficult to put in place due to the risk of pathogen growth and microbiological contamination typical of fresh food products (Plazzotta et al., 2017). On the other hand, Manzocco et al. (2016) elaborate on two other options for FLW reuse that are more appealing from a social point of view, since the reused products are still intended for human consumption. The first strategy is the donation of substandard raw materials, products resulting from overproduction or items not sold due to low prices but that are still safe for human consumption, according to the existing legal requirements. These products should be diverted to redistribution networks and given to food banks to help supply people in need. The second strategy to manage FLW is to turn an output into an input, i.e. allow FLW to re-enter the production cycle as a raw material or a semi-finished product. For example, fresh fruits and vegetables deemed unsuitable for consumption, due to over-ripening, size or shape, are being used for juice or jam production (Manzocco et al., 2016).

Prevention strategies, situated at the top of the food waste hierarchy, are considered to be the most environmentally favourable FLW management option (Papargyropoulou et al., 2014; Manzocco et al., 2016; Plazzotta et al., 2017). These strategies encompass the avoidance of surplus food and the prevention of avoidable FLW along FSCs. In sum, the prevention strategies translate into the reduction of FLW at the source. Though it may be difficult to reduce the generation of FLW in some situations, some changes can be easily implemented to eliminate the source of the problem. For instance, the surplus food purposely generated by agricultural production to respond to harvest losses due to natural phenomena may be difficult to eliminate, but strategies, like sharing information regarding the remaining shelf life or training staff for better product handling, are easier to implement. The focus of this thesis lies upon these strategies. The thesis is focused on the reduction of FLW along FSCs, preventing food from turning to waste, and not on re-use, recycling, recovery or disposal strategies to best manage the food discarded from FSCs.

In 2015, the United Nations developed the 2030 Agenda for Sustainable Development, adopted by all Member States, establishing 17 Sustainable Development Goals (SDGs) (UN General Assembly, 2015). The aim of SDG 12 is to "ensure sustainable consumption and production patterns" and goal 12.3 specifically calls for "halving per capita global food waste at retail and consumer levels and reducing food loss along production and supply chains, including post-harvest loss, by 2030" (UN General Assembly, 2015; Vittuari et al., 2016). In this context, minimizing FLW and using natural resources efficiently play a crucial role concerning the challenge to feed the world's population sustainably (FAO, 2019; Moraes et al., 2021).

The motivation to study FLW came from the importance that research and governmental entities were giving to this subject, but also from realising that research concerning the reduction of FLW could enable the efficient use of natural resources and contribute to a sustainable environment (Koester, 2014; Moraes et al., 2021). Moreover, reducing FLW could bring economic benefits to all members of FSCs and even for society, given that reducing FLW could translate into monetary savings (Moraes et al., 2021). In fact, the economic costs of FLW are quite substantial and amount to about USD 1 trillion per year (FAO, 2014). Nonetheless, FLW is associated with costs other than just economic ones. Generating FLW also has environmental impacts on the atmosphere, water, land and biodiversity that cost around USD 700 billion every year (FAO, 2014). Additionally, FLW is associated with social costs of around USD 900 billion annually, since it contributes to the degradation of the environment and to the depletion of natural resources, which will affect people's health and livelihood (FAO, 2014). These costs have to be paid by society and our future generations. Thus, successful efforts to reduce FLW can only be beneficial for our future.

Due to the magnitude of the problem and the emphasis that international governments have put on the reduction of FLW, research concerning FLW in FSCs has increased over time (Chauhan et al., 2021), particularly in the last decade. These studies have investigated the problem of FLW from different perspectives. Some studies have presented different methods to quantify the levels of FLW (e.g., Corrado and Sala, 2018; Kafa and Jaegler, 2021), assessing its environmental impacts (e.g., Porter et al., 2016) and more recently its economic impacts too (e.g., de Gorter et al., 2021). Some researchers have investigated the sources and drivers of FLW (e.g., Mena et al., 2014; Thyberg and Tonjes, 2016) and others have identified potential solutions to the problem (e.g., Diaz-Ruiz et al., 2019, Mesterházy et al., 2020), focusing their studies on different stages of FSCs (e.g., Redlingshöfer et al., 2017; de Moraes et al., 2020), on different geographies (e.g., Dal' Magro and Talamini, 2019; Bedoya-Perales and Dal' Magro, 2021) and on different food products (e.g., Willersinn et al., 2017; Xue et al., 2020).

But if this subject has already been so significantly researched, then why is it still a problem? What are the main hindrances to implementing efficient solutions? The literature provides several hints as to why FLW is still relevant globally. One obstacle to mitigating FLW along FSCs relates to the definition of FLW, since there are many different definitions for FLW encountered in the literature (Lemaire and Limbourg, 2019). Several authors state that the various different definitions of FLW reported in the literature clearly limit the comparability of the studies' results and is a barrier to the mitigation of FLW (Nahman and de Lange, 2013; Beretta et al., 2013; Halloran et al., 2014; Richter and Bokelmann, 2016; Calvo-Porral et al., 2017). Another gap encountered in the literature concerns the lack of clear knowledge about the real magnitude of FLW, making it difficult to measure progress against any FLW reduction target (Affognon et al., 2015). Despite the growing body of knowledge concerning FLW, the pattern and range of FLW along FSCs is not yet well understood (Bagherzadeh et al., 2014) and a scarcity of data concerning FLW, with estimates varying widely, is notable due to a lack of a uniformity or standardisation in methods to quantify FLW (Liu et al., 2016; Chauhan et al., 2021). Furthermore, there is a lot of data on FLW at the household stage for a variety of countries, while research on FLW generated during agricultural production, manufacturing and retail is much more limited, reflecting the focus of the literature on the downstream stages of FSCs (Bräutigam et al., 2014).

On the other hand, the literature still does not fully understand the causes of FLW along FSCs and there is still a need to understand their relative importance (Chauhan et al., 2021), since they are interconnected and depend on one another (Mena et al., 2011). Uncertain estimates of FLW, coupled with an imprecise understanding of the hotspots of FLW along FSCs, could lead to policy errors and to the selection and implementation of sub-optimal mitigation strategies of FLW (Affognon et al., 2015). Furthermore, the literature lacks investigations concerning the results of implementing the mitigation strategies of FLW, which limits the understanding of the practical applicability of the mitigation strategies (Schneider, 2013; Moraes et al., 2021; Chauhan et al., 2021). The availability of evaluation methodologies to assess the performance of those strategies is still limited (Schneider, 2013; Moraes et al., 2021) and very few report the environmental, economic, and social impacts of the mitigation strategies as well as their efficiency concerning the accomplishment of the targeted FLW reduction goals (Goossens et al., 2019). Moreover, there is a need to conduct more evidence-based research comparing the mitigation strategies for different food products, stages of FSCs and geographies (Chauhan et al., 2021). Overall, there is a need to develop appropriate methods to assess the effectiveness of the mitigation strategies of FLW to enable the identification of the best alternatives and the prioritisation of the most promising ones (De Laurentiis et al., 2020). Considering the gaps in the literature regarding the causes and the mitigation strategies of FLW, the aim of this thesis is to contribute to this body of knowledge (with a literature review done in Chapter 1 from Part I of this thesis and with the empirical analysis performed in part II). This contribution will be made by identifying and modelling the causes of FLW and by identifying, evaluating and ranking the mitigation strategies of FLW, while maintaining a holistic perspective of FSCs (analysing experts' opinions from production until retail) and assessing two countries with different levels of economic development (Portugal and Brazil) and two different fresh products (fruits & vegetables, and beef).

In addition to introducing the topic under study and contextualizing the motivation for pursuing this research, this introduction presents the research questions, main objectives, as well as the structure of the thesis and a summary of the methodologies applied. This clarifies the link between all the elements of the thesis and provides an overview of the study. The details of specific methodologies are presented in the individual chapters.

i. Research Questions

There is an agreement among researchers that in order to establish and implement effective measures to prevent FLW, one must know its causes and the mitigation strategies available to tackle them (Mena et al., 2011; Affognon et al., 2015; Chauhan et al., 2021; Vittuari et al., 2016; Priefer et al., 2016). Furthermore, the literature seems to indicate that the causes of FLW are dependent on the stage of FSCs considered, the regions under study and the food product under analysis (Martínez et al., 2014; Bräutigam et al., 2014; Arivazhagan et al., 2016). Thus, it is expected that the suitability of mitigation strategies should also be dependent on these three variables.

However, the gaps previously identified in the literature clearly suggest that the literature on these issues, causes and mitigation strategies of FLW, is still recent and inadequate. In fact, most previous studies on the causes or mitigation strategies of FLW have failed to consider the three variables referred to above, often focusing on a limited set of FSC stages, on a single product family and on a given region. Thus, there is a need to broaden our knowledge concerning the causes of FLW and the mitigation strategies that should be implemented to tackle them, taking into consideration the three main variables that can influence them. This led to the following research questions:

RQ1 – What are the main causes of FLW at the different stages of FSCs, for economies at different levels of development and for different food products?

RQ2 – Which mitigation strategies help to reduce FLW at the different stages of FSCs, for economies at different levels of development and for different food products?

Some previous studies have pointed out that the causes of FLW are not independent from each other (Mena et al., 2011). Indeed, some causes of FLW may be interrelated, meaning that acting upon a given cause may have a beneficial or detrimental effect upon other causes of FLW, which complicates the selection of the most promising mitigation strategies to reduce FLW along a specific FSC. However, even though there are some studies identifying the main causes of FLW for a given context or product, the interrelatedness between these causes has been little investigated in the literature. Therefore, to enable the selection of the most promising mitigation strategies of FLW, it is critical to first identify and model the interrelationships between the causes of FLW. Consequently, the following research question was drawn up:

RQ3 – How are the causes of FLW along fresh food supply chains interrelated?

The causes of FLW and their interrelatedness will be assessed for a Portuguese fruit and vegetable supply chain and for a Brazilian Beef supply chain to assess the impact that different contexts and food products have on the identification of the causes of FLW and on their interrelationships.

After identifying the root causes of FLW, it is necessary to identify the most promising mitigation strategies to tackle them. However, even though many strategies have been reported in the literature (e.g., Wunderlich and Martinez, 2018; Spang et al., 2019), very few studies have reported the strategies' environmental, economic, and social impacts or even their efficiency concerning FLW reduction (Schneider, 2013; Goossens et al., 2019; Redlingshöfer et al., 2020). They also do not include an analysis of the priority among the strategies (Fujii and Kondo, 2018). In sum, the study of the mitigation strategies for FLW is still at an early stage of development and appropriate methods to assess their effectiveness need to be developed to enable the identification of the best alternatives and the prioritisation of the most promising ones (De Laurentiis et al., 2020). Therefore, to finally assess which mitigation strategies should be implemented to tackle FLW along FSCs, the following research question was prepared:

RQ4 – How should the most promising mitigation strategies of FLW to tackle the known causes of FLW and reduce FLW along fresh food supply chains be identified, evaluated and prioritised?

ii. Research Objectives

The main purpose of this thesis is to contribute to the understanding of the phenomenon of FLW along fresh FSCs. The investigation is directed at the level of prevention within the food waste hierarchy, particularly seeking to promote the reduction of FLW along FSCs. Besides answering the previously defined research questions, the aim of this study is also to accomplish the following objectives:

- Contribute to the state of the art on the causes and mitigation strategies of FLW, for the different stages of FSCs, for countries with different levels of economic development and for different food products, by identifying what is already known and what needs to be further investigated on the topic (Chapter 1).
- Develop a research framework that researchers and stakeholders should implement in the future to determine the most promising mitigation strategies to reduce FLW along FSCs (Chapter 1).
- Test the research framework empirically in order to identify and model the interrelationships between the causes of FLW along FSCs (Chapters 2 and 3).
- Establish a connection between the causes of FLW identified and the potential strategies to mitigate the causes and reduce FLW along FSCs (Chapter 4).
- Test the research framework empirically to identify, evaluate and rank the mitigation strategies of FLW to select the most promising strategies to reduce FLW along FSCs (Chapter 4).

iii. Structure of the Thesis and Methodological Summary

This thesis encompasses two parts, besides the introduction and the conclusions.

Part I is composed of one chapters. Chapter 1 presents a systematic literature review of the causes and mitigation strategies of FLW and the development of a research framework to guide future investigations to study the mitigation strategies to implement to ensure an effective reduction of FLW in FSCs.

Part II is composed of three chapters and comprises the testing of the research framework developed in Part I. Chapter 2 provides empirical testing of the research framework to identify and model the interrelationships between the causes of FLW in the context of the Portuguese Fruit and Vegetable Supply Chain. Chapter 3 provides empirical testing of the research framework to identify and model the interrelationships between the causes of FLW in the context of the Brazilian Beef Supply Chain. The research framework was tested for two countries with different levels of economic development and for two different food products to validate the framework for different contexts. Chapter 4 provides empirical testing of the research framework to identify, evaluate and rank potential mitigation strategies based on the causes of FLW from Chapter 2.

The structure of this thesis is depicted in Figure *III*.

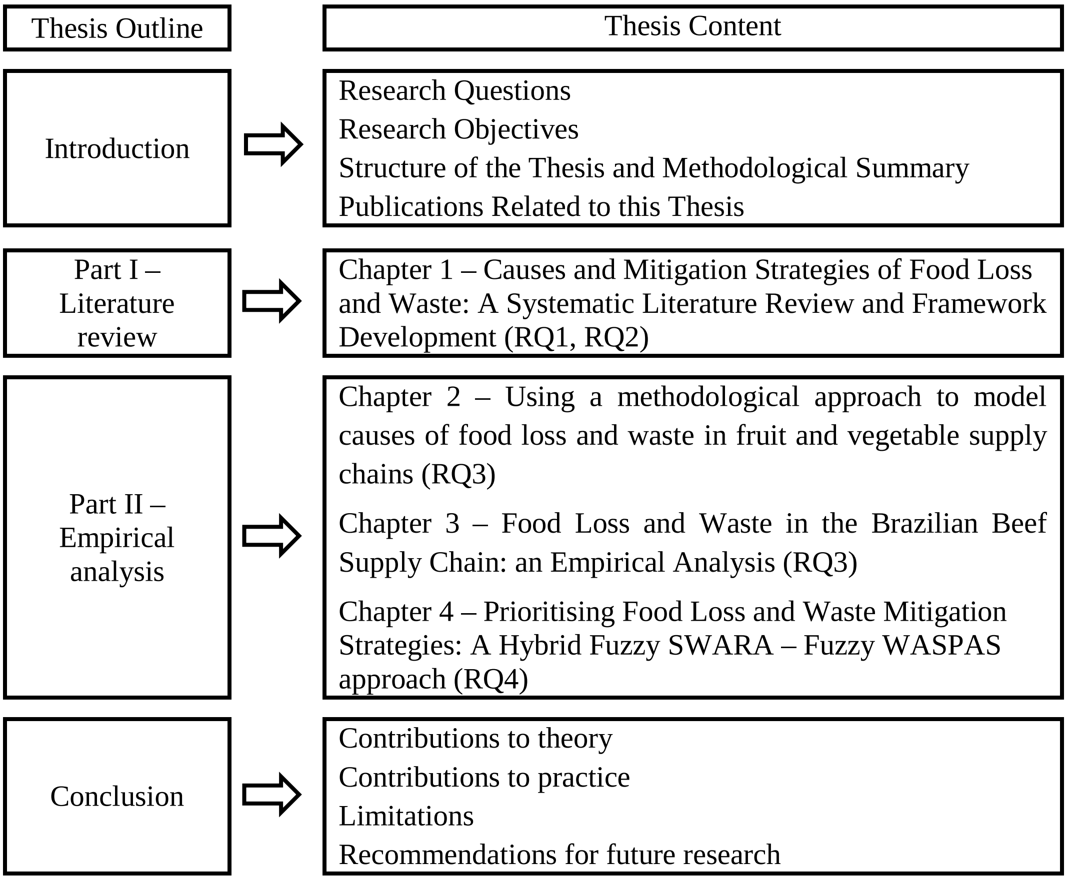

Figure III – Structure of the thesis.

Throughout the chapters of this thesis, different methods were used to achieve the objectives proposed and answer the research questions. A summary of the methodologies used in each part of the thesis is provided below in Table I. The detailed methodologies are presented in each chapter.

Table I – Summary of the methods employed in this thesis.

Part I – Literature review	**Part II – Empirical analysis**
• Systematic literature review methodology presented by Denyer and Tranfield (2009)	• Interpretive Structural Modelling (ISM) methodology (Venkatesh et al., 2015; Shen et al., 2016; Mishra et al., 2017; Kwak et al., 2018; Gan et al., 2018) • Matrix Impact of Cross Multiplication Applied to Classification (MICMAC) analysis (Shen et al., 2016; Gardas et al., 2017; Mishra et al., 2017; Gan et al., 2018) • Semi-structured interviews (Given, 2008; Harrell and Bradley, 2009) and Focus Group Discussion (FGD) research technique (Greenbaum, 1998; Nassar-McMillan and Borders, 2002) • Fuzzy Step-wise Weight Assessment Ratio Analysis (SWARA) method (Mavi et al., 2017; Zarbakhshnia et al., 2018; Perçin, 2019) • Fuzzy Weighted Aggregated Sum Product Assessment (WASPAS) method (Zavadskas et al., 2012; Turskis et al., 2015; Turskis et al., 2019; Agarwal et al., 2020)

Part I – Literature review

Chapter 1 is based on the systematic literature review method presented by Denyer and Tranfield (2009) that was used to identify the causes and mitigation strategies of FLW along FSCs. A systematic literature review helps to provide information and to synthesize knowledge on a certain research topic or field, enabling the identification of existing gaps in the literature and avenues for future work (Tranfield et al., 2003; Bhattacharya et al, 2021). Chapter 1 follows a three-stage approach: (1) planning, (2) conducting and (3) reporting the results of the review to produce a replicable and transparent literature review.

The results are discussed in two parts. In the first part, the causes of FLW are analysed at the different stages of FSCs and for the process of transporting food in between stages, establishing differences between developed and developing countries and between plant-based and animal-based supply chains. The second part presents a similar analysis performed for the causes of FLW, but this time it analyses the mitigation strategies of FLW, evidencing the differences between developed and developing countries and between plant-based and animal-based supply chains for the different stages of FSCs and for the process of transporting food in between stages. A research framework to guide future investigations that wish to study the mitigation strategies of FLW further, in order to implement and ensure an effective reduction of FLW in FSCs is developed.

Part II – Empirical analysis

The second part of this thesis consists of the empirical part.

The objective of chapters 2 and 3 is to test the steps of the research framework developed in Chapter 2 that identifies and models the interrelationships between the causes of FLW along FSCs. The methodology implemented in both chapters is very similar. Both chapters make use of a literature review to identify the causes of FLW for the context under analysis (Chapter 2 analyses the Portuguese fruit and vegetable supply chain and Chapter 3 the Brazilian beef supply chain). Afterwards, the Interpretive Structural Modelling (ISM) methodology is used to model the interrelationships between the causes of FLW and the Matrix Impact of Cross Multiplication Applied to Classification (MICMAC) analysis is used to identify which are the root causes of FLW for the context studied. The data, to enable the implementation of the ISM methodology and the MICMAC analysis, were collected by means of the Focus Group Discussion (FGD) research technique, for Chapter 2, and through semi-structured interviews, for Chapter 3. Experts from academia and from industry, including stakeholders from production until retail, were selected and invited to be part of each study to maintain a holistic understanding of the issue, as suggested by several authors in the literature (Beretta et al., 2013; Papargyropoulou et al., 2014; Thyberg and Tonges, 2016; Strotmann et al., 2017; Moraes et al., 2021).

Chapter 4 tests the steps of the research framework developed in Chapter 1 that identifies potential mitigation strategies of FLW, selects criteria to assess FLW prevention measures and evaluates and ranks the mitigation strategies. In this chapter, the fuzzy Step-Wise Weight Assessment Ratio Analysis (SWARA) was employed to determine the relative weights of the evaluation criteria selected to evaluate the performance of the mitigation strategies. The fuzzy Weighted Aggregated Sum Product Assessment (WASPAS) was implemented to rank the mitigation strategies. The work developed in this chapter was a continuation of the work begun in Chapter 2 and it joined together the same experts from Chapter 2 in a focus group to enable the data collection and the implementation of the fuzzy SWARA and fuzzy WASPAS methodologies.

iv. Publications Related to this Thesis

The publications and presentations presented in Table II resulted from the present research. Chapters 1 to 4 of this thesis resulted in articles that were either published or are currently under review in ISI indexed journals. The feedback received throughout the presentations of the papers at conferences and the reviewing processes of book chapters and articles helped to improve the final chapters presented in the thesis and to broaden its contributions to the field of research. The publications are presented in chronological order.

Table II – Publications related to the thesis.

Year	Type	Publication	Title
2017	Conference paper	Proceedings of the 47th International Conference on Computers & Industrial Engineering (CIE47), Lisbon, Portugal, 11-13 October 2017	An overview on the research status of the problem of food loss and waste along food supply chains
2019	Conference paper	Proceedings of the 26th EurOMA Conference: Operations Adding Value To Society, Helsinki, Finland, 17-19 June 2019	Modelling the causes of food loss and waste in fresh food supply chains: An integrated ISM-MICMAC analysis
2019	Book chapter	J. Reis et al. (eds.), Industrial Engineering and Operations Management I, Springer Proceedings in Mathematics & Statistics	Causes of Food Loss and Waste: An Analysis Along the Food Supply Chain
2021	Journal article	The International Journal of Logistics Management, Vol. 32, No. 1, pp. 214-236	Food loss and waste in the Brazilian beef supply chain: an empirical analysis
2021	Conference paper	Proceedings of the 8th EurOMA Sustainable Operations and Supply Chain Forum, Excelia Business School, La Rochelle, France, 22-23 March 2021	A framework for the prioritization of mitigation strategies of food loss and waste
2021	Journal article	Journal of Cleaner Production, Vol. 283, No. 124574	Using a methodological approach to model causes of food loss and waste in fruit and vegetable supply chains
2021	Conference paper	Proceedings of the 2021 International Conference on Resource Sustainability (icRS), Dublin, Ireland, 19 - 23 July 2021	Identifying the causes of food loss and waste in the Brazilian Beef Supply Chain
2021	Conference paper	Proceedings of the 2021 International Conference on Resource Sustainability (icRS), Dublin, Ireland, 19 - 23 July 2021	Reducing Food Loss and Waste: A Systematic Literature Review of Mitigation Strategies
2021	Conference paper	Proceedings of the 28th EurOMA Conference: Managing the "new normal" - The future of Operations and Supply Chain Management in unprecedented times, Berlin, Germany, 5-7 July 2021	A Framework to Reduce Food Loss and Waste along Food Supply Chains
2021	Journal article	Under review in an ISI indexed journal	Causes and Mitigation Strategies of Food Loss and Waste: A Systematic Literature Review and Framework Development
2021	Journal article	Under review in an ISI indexed journal	Prioritising Food Loss and Waste Mitigation Strategies: A Hybrid Fuzzy SWARA–Fuzzy WASPAS approach

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PART I – LITERATURE REVIEW

Part I aims to provide a clear view of the literature on the problem of food loss and waste along food supply chains, presenting a systematic literature review of the causes and the mitigation strategies of food loss and waste, taking into account different stages of the food supply chain, countries with different levels of economic development, and different food products, in Chapter 1. Besides contributing to the literature, this part of the thesis helps to identify the main research opportunities in the field and to develop a research framework to guide future investigations seeking to identify the most promising strategies to mitigate food loss and waste along food supply chains.

Chapter 1

Causes and Mitigation Strategies of Food Loss and Waste: A Systematic Literature Review and Framework Development

Abstract

One third of all food produced for human consumption ends up as food loss and waste (FLW) each year along the food supply chain (FSC). To prevent FLW, it is paramount to understand why food is being discarded and to identify the most appropriate mitigation strategies to implement along FSCs. In this paper, a systematic literature review approach was implemented to search and evaluate 114 peer-reviewed articles to analyse the causes and mitigation strategies of FLW. The primary focus was to classify and discuss the 80 causes and 73 mitigation strategies retrieved from the literature, taking into account the differences between: (1) different stages of FSCs, (2) countries with different levels of economic development, and (3) different food products. In conclusion, results show that the causes and the mitigation strategies of FLW have a managerial, infrastructural, behavioural or technological focus and that they are dependent on the stage of FSCs, the type of product and the level of economic development of the country under study. Moreover, some causes identified in some stages of FSCs are dependent on causes encountered in other stages, vindicating the reference, in the literature, to mitigation strategies that should be applied in various stages of FSCs. Thus, the choice of the most promising mitigation strategies to reduce FLW along FSCs is not straightforward and should take into account not only the context of the problem under study, but also the root causes of FLW, their interrelatedness and their influence over that context. Based on these findings, the paper proposes a research framework to guide future investigations that seek to further study the mitigation strategies to implement to ensure an effective reduction of FLW in FSCs.

Keywords: Causes of Food Loss and Waste; Mitigation Strategies; Transport; Food Products; Developed and Developing countries; Systematic Literature Review.

1.1. Introduction

Food loss and waste (FLW) sums one-third of the total food produced globally for human consumption, about 1.3 billion tons of food, squandering also the 0.9 million hectares of land and 306 cubic kilometres of water used in its production (Priefer et al., 2016; Bendinelli et al., 2020). FLW seems to represent not only a misuse of natural resources (such as fertilizer, cropland, fresh water and energy), but also a missed opportunity to feed the world's growing population, since the food production is expected to increase by 70% to meet the worldwide needs by 2050 (Arivazhagan et al., 2016; Wunderlich and Martinez, 2018). Furthermore, if we halved global FLW, an additional 1 billion people could be fed, which in turn had the potential to end world hunger, since there are an estimated 815 million hungry and undernourished people, primarily in developing countries (Wunderlich and Martinez, 2018). This is why the reduction of FLW has been on the agenda of many governmental entities in the past years. The European Parliament, for example, adopted a resolution to halve FLW by 2025 (Munesue et al., 2015) and the United States did the same for 2030 (Liu et al., 2016). However, the success of such initiatives requires a detailed understanding of what is causing FLW along the food supply chain (FSC) and the identification of the hotspots where this FLW occurs (Priefer et al., 2016; Caixeta-Filho and Péra, 2018).

Reducing FLW requires holistic and systemic changes in the production, processing, distribution and consumption of food (Mourad, 2016), yet, the most promoted solutions and dominant approaches often focus solely on the recycling, recovery or disposal of existing FLW and do so mainly for the later stages of FSCs (Liu et al., 2016). Even though prevention has been the least promoted solution so far, it is the most environmentally favourable option to manage FLW (Papargyropoulou et al., 2014; Plazzotta et al., 2017) and the best option from a long-term sustainable consumption and production perspective (Mourad, 2016). However, before designing and implementing effective prevention policies, a comprehensive knowledge concerning the causes of FLW is crucial (Vittuari et al., 2016).

Although FLW is a global issue, the ratio of FLW can vary significantly between: (1) the stages of FSCs (e.g., Shafiee-Jood and Cai, 2016), (2) countries with different levels of economic development (e.g., Martínez et al., 2014; Wunderlich and Martinez, 2018), and (3) different food products (e.g., Spang et al., 2019). Therefore, these three factors will influence the causes of FLW and the resultant mitigation strategies.

This article performs a systematic literature review to investigate the causes of FLW, as well as the strategies most suited to mitigate them, highlighting the differences between the different stages of FSCs, for developed and developing countries and for plant-based and animal-based food products. Afterwards, we discuss the main gaps encountered in the literature and the avenues for future work. To keep the scope of this review manageable, the consumption stage of FSCs is excluded, because the causes are mostly related to consumers' attitudes (Schanes et al., 2018) and there is already an extensive body of knowledge examining the: psychological, social, situational, demographic and socioeconomic factors of FLW at this stage (e.g., Stancu et al., 2016; Abdelradi, 2018; Gao et al., 2021). On the other hand, the process of transporting food along FSCs is investigated, since it has been overlooked by the literature, despite some reports showing that the levels of FLW within this process are not irrelevant. See for example Jedermann et al. (2014) that refers to berries loss during transportation or Miranda-de la Lama et al. (2014) and Mendonça et al. (2018) for the negative impact of animal transportation.

To sum up, two research questions (RQs) guided this review:

(RQ1) What are the main causes of food loss and waste in the different stages of food supply chains, for economies at different levels of development and for different food products?

(RQ2) Which mitigation strategies aid in reducing food loss and waste in the different stages of the food supply chain, for economies at different levels of development and for different food products?

This review is organised as follow: next section addresses the previous contributions to FLW literature, highlighting their limitations. Then, section 1.3, describes the research methodology adopted in this study. In section 1.4 we discuss the causes of FLW emphasising the discrepancies between countries with different levels of economic development, for different stages and processes of FSCs and for different food products. Section 1.5 is devoted to the mitigation strategies of FLW, discussing the particular needs of the different stages of FSCs, for developed and developing countries and for different food products to combat FLW. Section 1.6 discusses avenues for future research. Section 1.7 proposes a research framework to guide future investigations that seek to further study the mitigation strategies to implement to ensure an effective reduction of FLW in FSCs. Finally, the important findings and conclusions are drawn in section 1.8.

1.2. Growing Concerns about Food Loss and Waste

The problem of FLW has recently received greater attention worldwide, with the rise of news disseminated by the various media outlets, but also with the rise of researchers who have been trying to understand FLW along FSCs. In fact, there are already some literature reviews investigating what is causing and what can be done to mitigate FLW. These reviews are presented in Table 1.1.

Table 1.1 – Previously published reviews about FLW.

Authors	**Region**	**Causes**	**Mitigation Strategies**	**FSC Stages**	**Levels of Economic Development**	**Food Product**
Parfitt et al. (2010)	BRIC		✓			N/S
Hodges et al. (2011)	DC and UC	✓	✓		✓	N/S
Samuel et al. (2011)	Nigeria	✓	✓			Maize
Koester (2014)	N/S		✓	✓		N/S
Priefer et al. (2016)	Europe	✓				N/S
Thyberg and Tonjes (2016)	DC	✓				N/S
Shafiee-Jood and Cai (2016)	USA and SSA	✓	✓			N/S
Sibomana et al. (2016)	SSA	✓	✓			Tomato
Bernstad et al. (2017)	N/S	✓		✓		Tomato
Vilariño et al. (2017)	Global		✓			N/S
Wunderlich and Martinez (2018)	DC and UC	✓	✓		✓	N/S
Spang et al. (2019)	N/S	✓	✓	✓		N/S
de Moraes et al. (2020)	N/S	✓	✓			N/S
El Bilali and Hassen (2020)	GCC	✓	✓			N/S
Bhattacharya et al. (2021)	N/S	✓		✓		N/S
de Oliveira (2021)	N/S		✓			N/S
Dora et al. (2021)	DC and UC	✓	✓	✓	✓	N/S
Total:		13	13	5	3	

Note: DC – Developed Countries; UC – Developing Countries; BRIC – Brazil, Russia, India and China; SSA – Sub-Saharan Africa; GCC – Gulf Cooperation Council Countries (viz. Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates).; N/S – Not Specified.

From Table 1.1, it seems that a comprehensive literature review, considering the three factors influencing FLW causes and mitigation strategies: country economic development level, stages of FSCs and type of food product, is still missing. In fact, Table 1.1 shows that thirteen reviews investigate the causes of FLW and thirteen investigate the mitigation strategies, however only five made an analysis for the different stages of FSCs and only three discussed the differences between developed and developing countries. In addition, only three reviews target particular food products, but none investigated disparities between different food products. In summary, the previous reviews have some limitations when reporting the main causes of FLW and the strategies capable to mitigate the problem. These are mainly due to not considering the nuances between all the stages comprising FSCs, not specifying the geographical and economical context under which the studies were conducted, scantily elucidating the reader about the differences between developed and developing economies, and not investigating the causes and mitigation strategies for different food products.

To address these shortcomings, a systematic literature review will be performed in this paper to contribute to the body of knowledge regarding FLW by: (1) investigating the causes of FLW and the strategies most suited to mitigate them; (2) highlighting the differences between developed and developing countries; (3) addressing the different stages of FSCs and the process of transporting food between them; and (4) assessing the differences between plant and animal-based food products.

1.3. Methodology

This study adopted the systematic literature review (SLR) methodology presented by Denyer and Tranfield (2009) to identify the causes and mitigation strategies of FLW along FSCs. The SLR methodology helps to provide information and to synthesize knowledge on a certain research topic or field, enabling the identification of existing gaps in the literature and the avenues for future work (Tranfield et al., 2003; Bhattacharya et al, 2021). Moreover, the SLR methodology enables to produce a replicable and transparent literature review, consisting mainly of a three-stage approach: (1) planning, (2) conducting and (3) reporting the results of the review (Denyer and Tranfield, 2009). With that in mind, the review process began by identifying relevant, peer reviewed literature regarding the issue under study.

1.3.1 Research criteria and data collection

The first step towards the identification of relevant literature regarding the causes and mitigation strategies of FLW started with the definition of keywords to search the databases. An initial sample of studies focusing on the topic of FLW were used to determine the appropriate keywords to use and to compile the strings to input in the databases (Table 1.2). The keywords comprised a combination of terms related to “Food loss and waste”, “Perishability” “Supply chain”, “Causes” and “Mitigation Strategies” and the databases used to search for relevant literature were the Web of Science (WoS) and Scopus databases. The search was limited to studies published between 1990 and February of 2021, in the English language and excluding international conference proceedings and book chapters. The initial search results are presented in Table 1.2. After removing the duplicates from the initial search in the databases, 6.599 articles were selected and their information were exported to .CVS files to enable further analysis. A preliminary screening was performed on these articles, by reading their titles and, if needed, their abstracts and assessing if they contributed to the discussion regarding the causes and mitigation strategies of FLW in FSCs. Articles focusing on the disposal or valorisation of FLW, instead of its prevention and reduction, and studying the consumption stage of FSCs were not considered in this review. Using this criterion, 215 articles were selected for a full text analysis. From the full text analysis and using the same criterion, only 114 articles were considered relevant to answer our research questions (see Appendix A for more info on the articles selected). The selection process is summarised in Figure 1.1. The three authors evaluated the articles separately to ensure the reliability of the selection process. Any disagreement was debated until a consensus was reached and the articles were only selected if the three agreed.

Table 1.2 – Initial search on the databases.

Search string	Nr. articles	
	WoS	**Scopus**
(("food loss*" OR "food wast*” OR "food supply chain") AND ("cause*"))	985	1.186
(("food loss*" OR "food wast*" OR "food supply chain") AND ("reduc*") AND ("action" OR "measure*" OR "mitigation strateg*"))	615	870
(("food loss*" OR "food wast*") AND ("supply chain" OR "logist*" OR "transport*") AND ("cause*"))	160	224
(("food loss*" OR "food wast*") AND ("supply chain" OR "logist*" OR "transport*") AND ("action" OR "measure*" OR "mitigation strateg*"))	180	301
(("food loss" OR "food waste" OR "perishab*") AND ("prevent*" OR "reduc*"))	5.179	6.191

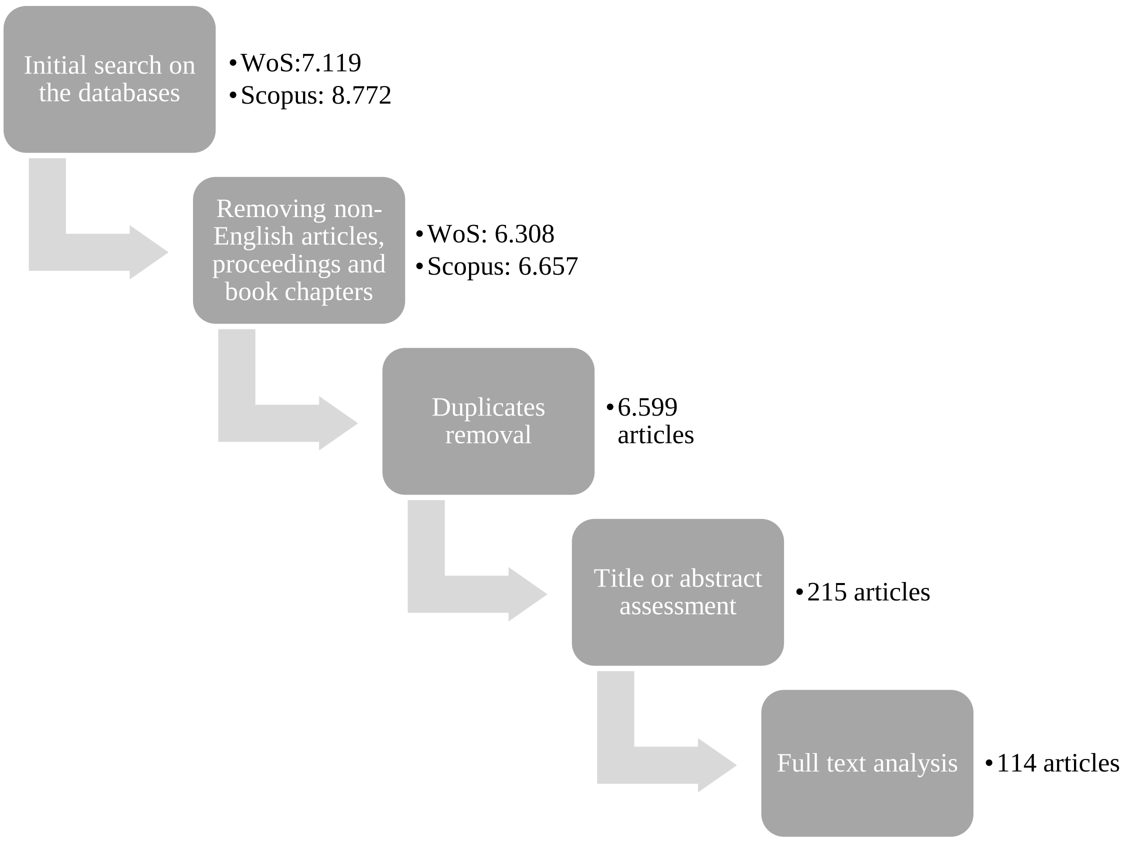

Figure 1.1 – Selection of the articles.

1.3.2 Bibliometric analysis

Figure 1.2 shows the evolution of the number of publications per year and it suggests that the interest in the issue increased mainly after 2010. Indeed, 94.7% of all articles were published after this year with an average of 9.8 publications per year. The lower number of studies published in 2020, when compared to the previous years, can be explained by the delays in research promoted by the COVID-19 pandemic, especially considering that more articles were already published in the first two months of 2021 than in 2020. The interest in researching FLW started several years before the UN developed the 2030 Agenda for Sustainable Development, which was adopted by all United Nations Member States in 2015, but it coincided with the Food and Agriculture Organization's report published in 2011, with the first attempt to gather information and measure the levels of FLW around the globe (FAO, 2011).

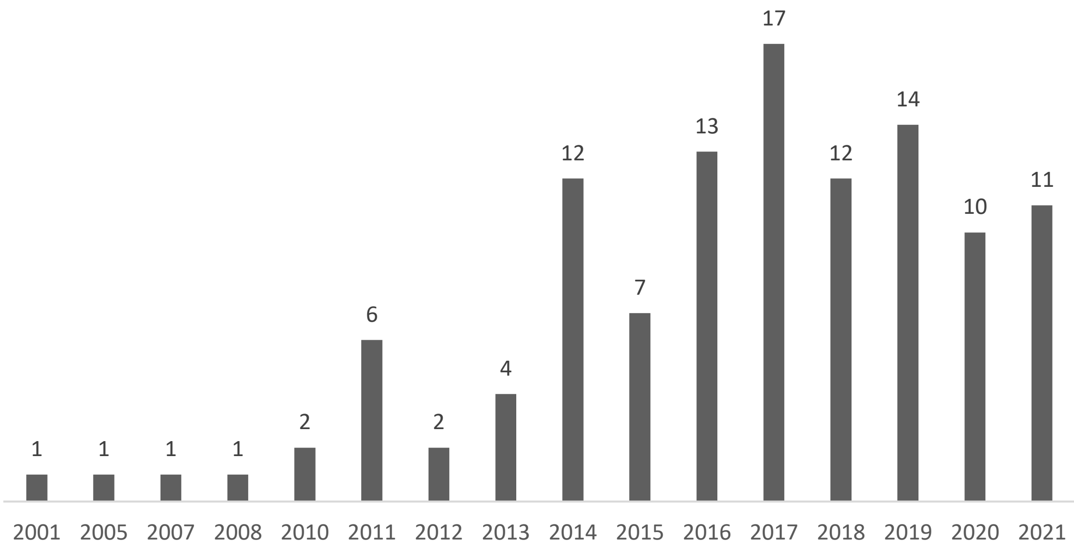

Figure 1.2 – Number of articles per year.

The articles were featured in 66 different journals and the most relevant outlets are depicted in Figure 1.3. These represent only 15% of the total number of journals, but they published roughly 50% of the papers analysed. According to the source areas by SciMago, these journals concern mainly agricultural and biological sciences and business, management and accounting.

Figure 1.3 – Most publishing journals.

Figure 1.4 depicts the most productive authors and Figure 1.5 presents the most productive institutions, from a set of 200 different institutions (retrieved from the authors' affiliations and comprising universities, research labs, non-profit organisations, enterprises, etc.) involved in the publication of the 114 articles reviewed. The figure shows that Brunel University and Wageningen University were the most productive institutions, involved in roughly 10.5% of the selected articles.

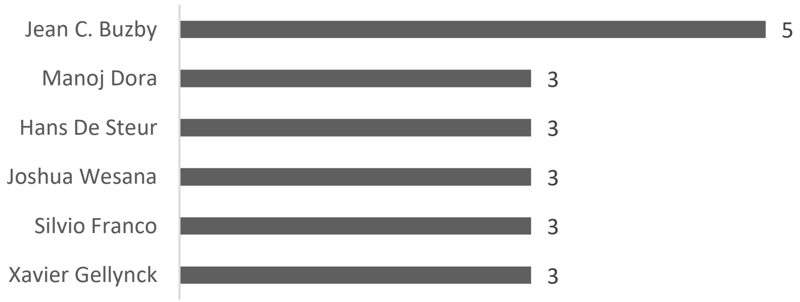

Figure 1.4 – Most productive authors.

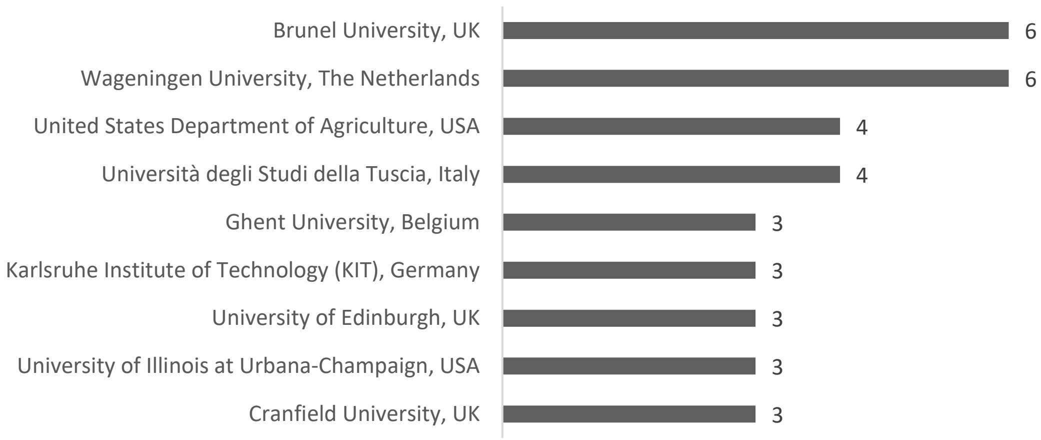

Figure 1.5 – Intitutions involved in the largest number of articles.

Figure 1.6 depicts the countries or regions studied in two or more articles and clearly shows the focus that has been given in the literature to developed countries, as opposed to developing ones. USA, Italy and UK are the most investigated countries, being investigated in roughly a quarter of the selected articles. When it comes to the stages of the supply chain, Figure 1.7 shows that the biggest portion of the selected articles kept a supply chain perspective, followed by the articles that did not specified the focus of their study (referred as N/S – Not Specified). However, the majority of the selected articles targeted smaller parts of FSCs, from which most of these focused on individual stages of FSCs, particularly the distribution stage that entails retailers and wholesalers.

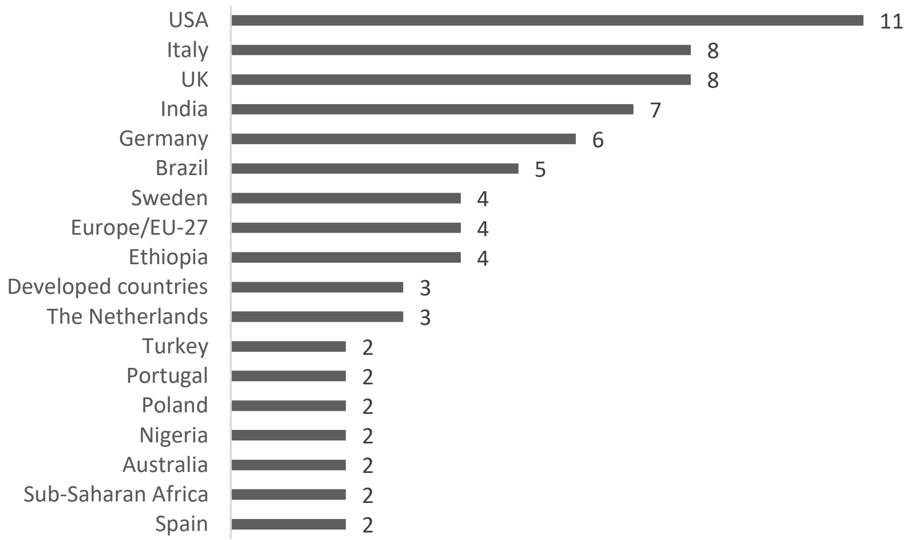

Figure 1.6 – Countries/regions studied in the articles.

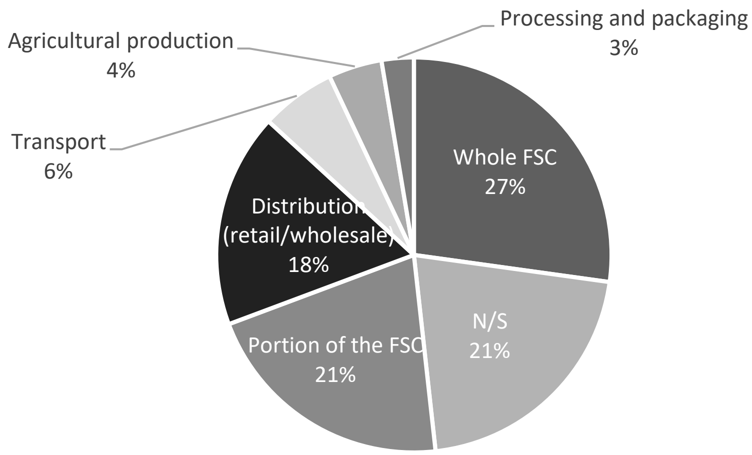

Figure 1.7 – Stages of FSCs studied in the articles.

1.4. Causes of Food Loss and Waste along Food Supply Chains

The different stages of FSCs investigated in this review are illustrated in Figure 1.8 and are considered the typical stages of FSCs in many other works (e.g., Munesue et al., 2015 and Bernstad et al., 2017). The process of transporting food products along FSCs is also investigated in this paper to analyse the causes of FLW in-between the stages, since this is a process often overlooked in the literature. Even though the available literature investigates the distribution stage, this stage also includes many other activities not directly related to the movement of food products along FSCs (Lipinska et al., 2019). Also, as previously mentioned, the authors decided to leave the consumption stage out of this study to keep the scope of this review manageable, since it has already been vastly investigated in the literature (e.g., Stancu et al., 2016; Abdelradi, 2018; Gao et al., 2021).

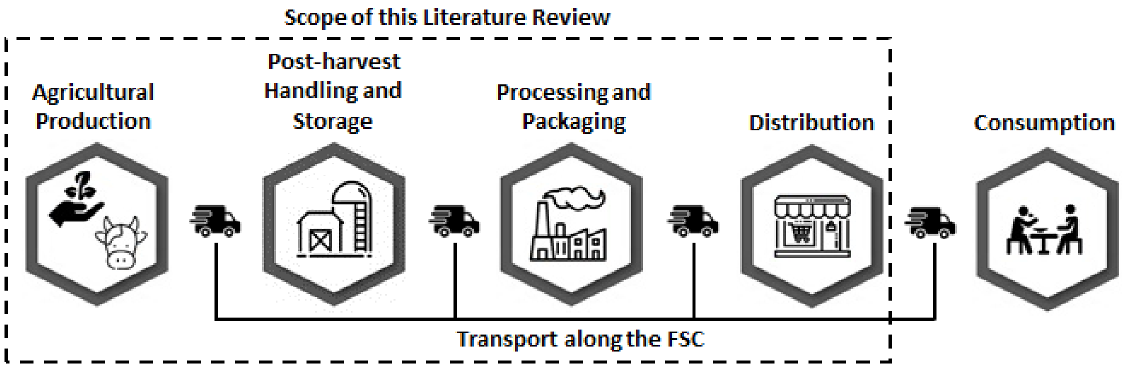

Figure 1.8 – Typical stages of FSCs.

1.4.1 Agricultural Production

This is the first stage of FSCs and includes the time from planting to harvesting. FLW at the agricultural stage is often generated due to mechanical damage and/or spillage during harvesting and sorting out crops directly after harvesting (Martínez et al., 2014; Bernstad et al., 2017). Farmers frequently leave crops in the field or plough them into the soil to avoid incurring more expenses, to cope with market prices' fluctuation due to overproduction (Martínez et al., 2014; Corrado et al., 2017). Furthermore, crops that do not meet quality standards regarding the shape, size, colour, and ripening are also left to rot in the fields. The quality can also be compromised due to improper storage and temperatures' maintenance, bad sanitation, exposition to light, inadequate levels of moisture and oxygen, and adverse environmental conditions that may lead to pests and diseases (Martínez et al., 2014).

The causes of FLW encountered in the literature for the agricultural production stage of FSCs are listed in Table 1.3 and are divided by developed and developing countries and by plant-based (P) or animal-based (A) food products. The absence of a check mark means that the articles did not mention the food product under study (see Appendix A for more details). The shaded causes of FLW identify the ones that are common to both developed and developing countries.

Table 1.3 – Causes of FLW in the Agricultural Production stage.

Causes	P	A	References	
Crops not harvested due to low market price	✓		Priefer et al. (2016); Calvo-Porral et al. (2017); Chen and Chen (2018); Johnson et al. (2019); Spang et al. (2019)	**Developed Countries**
Government food safety regulation			Buzby and Hyman (2012); Cicatiello et al. (2016)	
Limited technical support and technical errors			Chen and Chen (2018)	
Overproduction due to supply agreements with retail			Priefer et al. (2016); Dora et al. (2021); Messner et al. (2021); Jeswani et al. (2021)	
Equipment or technical malfunctions	✓	✓	Buzby et al. (2015); Cicatiello et al. (2016) ; Priefer et al. (2016); Corrado et al. (2017); Principato et al. (2019); Joensuu et al. (2020); Fernandez-Zamudio et al. (2020)	
Product sorted out due to industry's quality standards (e.g., weight, size, shape and appearance)	✓		Buzby and Hyman (2012); de Steur et al. (2016); Priefer et al. (2016); Chen and Chen (2018); de Hooge et al. (2018); Porter et al. (2018); Gillman et al. (2019); Johnson et al. (2019); Muth et al. (2019); Schneider et al. (2019); Spang et al. (2019); Joensuu et al. (2020); Fernandez-Zamudio et al. (2020); Messner et al. (2021); Jeswani et al. (2021)	
Push production systems			de Steur et al. (2016)	
Developing countries				
Inadequate demand forecasting and/or product ordering	✓		Buzby and Hyman (2012); Buzby et al. (2015); de Steur et al. (2016); Calvo-Porral et al. (2017); Gardas et al. (2017); Chen and Chen (2018); Dora et al. (2021)	
Labour shortages	✓		Chen and Chen (2018); Kuyu et al. (2019); Joensuu et al. (2020)	
Pest infestations, germs outbreaks and microbes contaminations	✓	✓	Abass et al. (2014); Mena et al. (2014); Corrado et al. (2017); Emana et al. (2017); Parmar et al. (2017); Tostivint et al. (2017); Kazancoglu et al. (2018); Johnson et al. (2019); Spang et al. (2019); Fernandez-Zamudio et al. (2020); Jeswani et al. (2021)	
Improper handling or spillages	✓	✓	Macheka et al. (2013); Buzby et al. (2015); Calvo-Porral et al. (2017); Tostivint et al. (2017); An and Ouyang (2019); Muth et al. (2019)	
Damages by insects, rodents, birds	✓	✓	Buzby and Hyman (2012); Abass et al. (2014); Mena et al. (2014); Papargyropoulou et al. (2014); Buzby et al. (2015); An and Ouyang (2019); Fernandez-Zamudio et al. (2020); Luo et al. (2021); Jeswani et al. (2021)	
Seasonality	✓		Buzby et al. (2015); Gokarn and Kuthambalayan (2017)	
Short product shelf life	✓	✓	Abass et al. (2014); Mena et al. (2014)	
Supply chain inefficiencies (e.g., lack of cooperation, coordination, trust and SC contracts)	✓	✓	Francis et al. (2008); Buzby et al. (2015); Gokarn and Kuthambalayan (2017); Chen and Chen (2018); Kolawole et al. (2021)	

	Weather-related produce damages (e.g., droughts, floods, hurricanes, and freezes)	✓	✓	Buzby and Hyman (2012); Macheka et al. (2013); Mena et al. (2014); Emana et al. (2017); Chen and Chen (2018); An and Ouyang (2019); Johnson et al. (2019); Schneider et al. (2019); Spang et al. (2019); Joensuu et al. (2020); Fernandez-Zamudio et al. (2020); Luo et al. (2021); Jeswani et al. (2021)
	Inadequate technologies for cultivation and harvesting	✓		Balaji and Arshinder (2016); Emana et al. (2017); Gokarn and Kuthambalayan (2017); Wunderlich and Martinez (2018); Kuyu et al. (2019); Dora et al. (2021)
	Lack of agricultural and economic infrastructures			Wunderlich and Martinez (2018); Dora et al. (2021)
	Lack of vertical integration between farmers and consumers	✓		Gardas et al. (2017)
	Premature harvesting	✓		Munesue et al. (2015); Irani and Sharif (2016); Sibomana et al. (2016)
	Stage of fruit maturity	✓		Macheka et al. (2013); Emana et al. (2017)

Most researchers agree that FLW is more evident in developed countries, namely at the consumer stage, when compared to developing ones, where the problem is more relevant in the early stages of FSCs (Parfitt et al., 2010; Hodges et al., 2011; Bräutigam et al., 2014; Garrone et al., 2014; Martínez et al., 2014; Plazzotta et al., 2017). However, Table 1.3 shows that the causes experienced at this stage in developed countries (7 causes) are more than the ones encountered for developing ones (5 causes). This can mean two things, either the causes for developing countries (the 5 specific, plus the 9 in common) lead to greater levels of FLW in these countries than in developed ones, or this is just a reflection of the fact that developing countries have been targeted by fewer studies in the literature. Despite that, the majority of the causes of FLW experienced in developed countries seem to be linked to decisions taken at other stages of FSCs, like the government regulations or the industries quality standards leading to rejections. In developing countries, the problem is linked to the lack of infrastructures or technology implementation, and to a lack of knowledge or training regarding for example the ideal time of harvesting or the ideal stage of maturity for harvesting. This suggests that the most appropriate mitigation strategies of FLW must be different for developed and developing countries, in the agricultural production stage.

From the 21 causes of FLW identified, sixteen relate to plant and seven to animal-based food products, mainly because plant-based products, particularly fruits and vegetables, have been largely studied in the literature in detriment of animal-based food products, like meat (see Appendix A for more info). However, this could also indicate that the causes of FLW at agricultural production are reliant of the food product. The table shows that the causes for animal-based products are common for developed and developing countries and that the challenges for breeding animals are very similar despite the level of economic development of the countries.

1.4.2 Post-harvest Handling and Storage

The post-harvest handling and storage stage includes activities such as handling, sorting and storage of food products. FLW is generated due to spillages, degradation and cold chain interruptions during handling and storage on the farm or between the farm and the processing facilities or retailers (Priefer et al., 2016; Bernstad et al., 2017; Corrado et al., 2017). Products may be removed due to quality standards (Priefer et al., 2016; Beausang et al., 2017; Calvo-Porral et al., 2017) or damaged by improper stacking, filling, cushioning (Macheka et al., 2013) and packaging (Priefer et al., 2016).

Table 1.4 depicts the causes of FLW taken from the literature for the post-harvest and handling stage of FSCs, for developed and developing countries and by plant-based or animal-based food products.

Table 1.4 – Causes of FLW in the Post-harvest Handling and Storage stage.

	Causes	**P**	**A**	**References**
Developed Countries	By-products from food processing not diverted to other food uses (e.g., ingredients)			Buzby and Hyman (2012); Alexander et al. (2017)
Developed Countries	Excess stock due to take-back agreements and orders' cancellations	✓		Priefer et al. (2016); Brancoli et al. (2019)
Developed Countries	Product rejected due to minimum food safety standards (e.g., pesticide residues)			Priefer et al. (2016)
Developed Countries	Equipment or technical malfunctions	✓		Buzby et al. (2015)
Developed Countries	Inadequate packaging	✓		Buzby et al. (2015)
Developed Countries	Product sorted out due to quality standards concerning weight, size, shape and appearance			Priefer et al. (2016); Calvo-Porral et al. (2017)
Developed Countries	Short product shelf life			de Steur et al. (2016); Gadde and Amani (2016)
Developed Countries; Developing countries	Improper handling or spillages	✓		Macheka et al. (2013); Buzby et al. (2015); Luo et al. (2021)
Developed Countries; Developing countries	Interruption of the cold chain	✓	✓	Macheka et al. (2013); Papargyropoulou et al. (2014); Calvo-Porral et al. (2017); Corrado et al. (2017); Gokarn and Kuthambalayan (2017); Caixeta-Filho and Péra (2018); Kazancoglu et al. (2018); Salihoglu et al. (2018); Wunderlich and Martinez (2018)
Developed Countries; Developing countries	Improper stacking and overfilled bins	✓	✓	Macheka et al. (2013); Mena et al. (2014); Buzby et al. (2015); Wohner et al. (2019)
Developing countries	Microbes and other contaminations during storage	✓	✓	Abass et al. (2014); Tostivint et al. (2017); Wunderlich and Martinez (2018); Kolawole et al. (2021)
Developing countries	Poor storage conditions and insufficient storage facilities	✓		Munesue et al. (2015); Balaji and Arshinder (2016); Gardas et al. (2017); Gokarn and Kuthambalayan (2017); Salihoglu et al. (2018); Wunderlich and Martinez (2018)
Developing countries	Product damaged by rodents/insects	✓		Samuel et al. (2011)

Thirteen causes of FLW were identified in the literature, from which seven were only experienced in developed countries, three in developing ones and three by both. The situation is very similar with the agricultural production stage. There are more causes identified for developed countries, evidencing the focus of the literature in these countries, and the causes experienced are somewhat linked to decisions taken elsewhere.

In developing countries, there are delays in storing the food products after harvest, often due to the lack of infrastructures, and the poor storage conditions lead to bad sanitisation. In contrast, the food products in developed countries are stored right after harvest, not evidencing infestation, rodent or weather-related damages. The duality of problems faced by developed and developing countries highlights the need for mitigation strategies that are tailored to the different economic contexts.

When it comes to the food products, nine causes relate to plant and three relate to animal-based products, showing that either the causes of FLW at this stage are very dependent on the food product or that there is a deeper understanding of FLW for plant-based supply chains, since these have been further investigated in the literature.

1.4.3 Processing and Packaging

The processing and packaging stage of FSCs refers to the reception, sorting and storage of raw materials in the processing facilities and the packaging and storage of processed products that will await transportation to the wholesalers' and retailer's outlets. It also includes the series of activities of food transformation, such as adding chemicals or other substances to increase shelf life and/or transforming them into new products.

FLW at this stage includes trims and degradation that occurs when products are not appropriate for processing, during the cleaning, peeling, chopping and boiling stages or even during procedure disruption and spills. It also includes rejections due to market requirements like quality, size, or quantity. In meat processing, FLW refers to trimmings and/or spillages during slaughtering and industrial processing. For fish, FLW is linked to industrial processing, such as canning or smoking. When it comes to milk, FLW relates to spillages during industrial milk treatment and to milk processing for cheese and yogurt (Martínez et al., 2014; Bernstad et al., 2017).

The full list of causes of FLW in the processing and packaging stage, for developed and developing countries and by plant-based or animal-based food products, can be consulted in Table 1.5.

Table 1.5 – Causes of FLW in the Processing and Packaging stage.

Countries	Causes	P	A	References
Developed Countries	Excess stock due to take-back agreements and orders' cancellations			Priefer et al. (2016)
Developed Countries	Inadequate inventory management	✓	✓	Mena et al. (2014)
Developed Countries	Overproduction of supermarket's own brands that cannot be sold elsewhere			Priefer et al. (2016)
Developed Countries	Equipment or technical malfunctions	✓	✓	Cicatiello et al. (2017); Dora et al. (2020); Principato et al. (2019)
Developed Countries	Interruption of the cold chain	✓	✓	Buzby et al. (2015); Corrado et al. (2017)
Developed Countries	Product rejected due to minimum food safety standards (e.g., pesticide residues)			de Steur et al. (2016); Priefer et al. (2016); Luo et al. (2021)
Developed Countries	Short product shelf life			de Steur et al. (2016)
Developed Countries	Wrong labelling	✓	✓	Mena et al. (2014)
Developed Countries / Developing countries	Inadequate or damaged packaging	✓	✓	Papargyropoulou et al. (2014); Buzby et al. (2015); Balaji and Arshinder (2016); Cicatiello et al. (2016); Priefer et al. (2016); Corrado et al. (2017); Gardas et al. (2017); Salihoglu et al. (2018); Spang et al. (2019); Wohner et al. (2019); Dora et al. (2020)
Developed Countries / Developing countries	Improper handling or spillages	✓	✓	Buzby et al. (2015); Corrado et al. (2017); Dora et al. (2020); Kolawole et al. (2021)
Developed Countries / Developing countries	Inefficient manufacturing processes	✓	✓	de Steur et al. (2016); Dora et al. (2020); Dora et al. (2021); Jeswani et al. (2021)
Developed Countries / Developing countries	Product sorted out due to industry's quality standards (e.g., weight, size, shape and appearance)	✓	✓	de Steur et al. (2016); Priefer et al. (2016); Calvo-Porral et al. (2017); Wunderlich and Martinez (2018); Abualtaher and Bar (2020); Dora et al. (2021); Messner et al. (2021); Luo et al. (2021); Jeswani et al. (2021)
Developing countries	Lack of adequate processing facilities	✓		Munesue et al. (2015); Gardas et al. (2017); Sibomana et al. (2016)
Developing countries	Poor processing practices and methods	✓		Balaji and Arshinder (2016); Gardas et al. (2017)
Developing countries	Product damaged by improper stacking			Macheka et al. (2013)
Developing countries	Non-adherence to standard and procedures	✓		Kolawole et al. (2021)

Sixteen causes of FLW were identified in the literature, from which eight are only reported in developed countries, four in developing ones and four in both. In developed countries, FLW is generated mainly as a result of: inefficiencies of the processing and packaging stage, overproductions and orders' cancellations, or safety and quality standards. Apart from the inefficiencies of the process itself, the other causes are, once again, dependent on decisions taken elsewhere. On the other hand, in developing countries, a lack of processing facilities allied to the products' seasonality, decreases this stage ability to process and store all of the production required, causing FLW (Martínez et al., 2014). This is aggravated by the fact that developing countries do not have the means or the willingness to invest in processing and storage facilities that will only be used during high season. Other experienced causes are related to inefficient processing practices and to the storage and handling of food products, with products damaged due to inadequate and damaged packaging or improper stacking. The latter causes were also experienced in the post-harvest and handling stage.

From the 16 causes of FLW identified, eleven are related to plant-based and eight to animal-based food products. The fact that the seven causes highlighted for animal-products, were also experienced in plant-based supply chains, suggests that the causes of FLW at this stage are less influenced by the type of food product.

1.4.4 Distribution

The distribution stage of FSCs refers to a set of operations that make food available for consumers and represents the market system (e.g., wholesale markets, supermarkets, retailers and wet markets). These operations are based on the supply and demand of food products and are responsible for assigning correct prices according to consumers' purchasing and habits, market agreements with producers and food availability (Martínez et al., 2014).

FLW at this stage usually encompasses products that remained unsold for a certain period, which may not be sold due to legal restrictions, even though they may still be fit for human consumption. The quality and aesthetic requirements either imposed by the retailers on their suppliers, or imposed by consumers, leads to rejections upon delivery or in-store (Martínez et al., 2014; Corrado et al., 2017). Other managerial decisions like the take-back agreements or last-minute order cancellations are responsible for substantial amounts of waste. These compel the suppliers of food products to remove from the shelves products that have already completed 75% of their shelf life, which, in turn, promotes these food products reaching the end of their shelf life without being sold (Martínez et al., 2014). Consumers seem to have a tendency to buy more food products from a fully stocked display rather than from a scantly filled container. This behaviour leads to overstocking and over-handling by both staff and consumers causing blemishes on the product displayed, and damaging food products at the bottom of the stack from the accumulated weight (Martínez et al., 2014). In summary, the marketing strategies used to attract customers, and the behaviour consumers' show when buying products with a good quality and price, directly affect the levels of FLW at the retail stage of FSCs (Martínez et al., 2014). The complete list of causes of FLW for the distribution stage of FSCs, for developed and developing countries and by plant-based or animal-based food products, may be consulted in Table 1.6.

Table 1.6 presents 23 different causes of FLW for the distribution stage. From these, eleven were reported in developed countries, four in developing ones and eight were reported by both. The increase in the number of causes experienced in developed countries compared to previous stages is noticeable, corroborating the agreement in the literature about FLW occurring mainly at the downstream stages of FSCs (Bräutigam et al., 2014). For these countries, the causes are more varied and more difficult to categorise or aggregate. Some causes are related to management decisions (like inefficient in-store management, pricing strategies and promotions management or inadequate demand forecasting and product ordering), others to government legislation (like rejections due to food safety standards), others to the characteristics of the products itself (like the seasonality of some goods or the sprouting and biological aging of fresh products), or even to consumers' preferences and behaviours inside the store (like rejections due to quality standards or confusing best before, use-by or sell by dates). For developing countries, the situation is completely different, given that FLW is caused mainly by inadequate market systems and the inefficient procurement channels. For developing countries, FLW is generated because the retail or wholesale facilities do not provide proper storage and lack sanitary and cooling conditions, compromising the quality of the products and their shelf life. While in developed countries, selecting or designing strategies to mitigate FLW in distribution is not easy, since the generation of FLW is linked to causes whose responsibilities are associated with different players of FSCs, the solutions to reduce FLW in developing countries should be linked to the improvement of the market systems and the procurement channels.

The causes of FLW at this stage seem to be independent from the food products, since the majority of them were experienced for both plant and animal-based products. From the 23 causes identified, 21 causes are related to plant-based and 16 to animal-based food products, indicating that there is not a clear focus on plant-based products, unlike in other stages of FSCs. This is explained by the fact that case studies, targeting the retail stage of FSCs, often evaluate the majority of the portfolio of products available in said retail store, analysing both plant (bread, fruits and vegetables, etc.) and animal-based (meat, fish, etc.) food products (see Appendix A for more info).

Table 1.6 – Causes of FLW in the Distribution stage.

Causes	P	A	References	
Consumers' confusion regarding best before/use-by/sell-by dates	✓		Buzby et al. (2015); Priefer et al. (2016); Calvo-Porral et al. (2017)	**Developed Countries**
Product rejected due to minimum food safety standards (e.g., pesticide residues)			Priefer et al. (2016)	
Inefficient in-store management (e.g., visual stocking, display and back-store)	✓	✓	Mena et al. (2011); Buzby et al. (2015); Mena et al. (2014); Calvo-Porral et al. (2017)	
Inefficient inventory management	✓	✓	Mena et al. (2011); Mena et al. (2014); Calvo-Porral et al. (2017)	
Low turnovers, inadequate batch sizes and SKU proliferation	✓	✓	Mena et al. (2014)	
Near or end of expiration date	✓	✓	Mena et al. (2011); Buzby et al. (2015); Calvo-Porral et al. (2017); Chen and Chen	

				(2018); Muth et al. (2019); Cicatiello et al. (2020); Dora et al. (2021); Horoś and Ruppenthal (2021); Luo et al. (2021); Jeswani et al. (2021)
	Pricing strategies and promotions management	✓	✓	Mena et al. (2011); Buzby et al. (2015); Mena et al. (2014); Priefer et al. (2016)
	Equipment or technical malfunctions	✓	✓	Mena et al. (2011); Buzby and Hyman (2012); Cicatiello et al. (2020)
	Retailer inflexibility in promotions (i.e., cannot turn around quickly)	✓	✓	Mena et al. (2014)
	Seasonality (e.g., holiday foods)	✓	✓	Buzby and Hyman (2012); Priefer et al. (2016); Cicatiello et al. (2020)
	Wide range of products and brands			Munesue et al. (2015)
Developing countries	Inadequate demand forecasting and/or product ordering	✓	✓	Mena et al. (2011); Buzby and Hyman (2012); Buzby et al. (2015); de Steur et al. (2016); Priefer et al. (2016); Gardas et al. (2017); Bilska et al. (2018); Chen and Chen (2018); Spang et al. (2019); Cicatiello et al. (2020); Dora et al. (2021); Luo et al. (2021); Jeswani et al. (2021)
	Interruption of the cold chain	✓	✓	Buzby and Hyman (2012); Calvo-Porral et al. (2017); Bilska et al. (2018); Spang et al. (2019); Cicatiello et al. (2020); dos Santos et al. (2020); Dora et al. (2021); Horoś and Ruppenthal (2021)
	Inadequate or damaged packaging	✓	✓	Mena et al. (2011); Buzby and Hyman (2012); Priefer et al. (2016); Calvo-Porral et al. (2017); Bilska et al. (2018); Principato et al. (2019); Horoś and Ruppenthal (2021); Silapeux et al. (2021); Luo et al. (2021); Jeswani et al. (2021)
	Improper handling or spillages (both by staff and consumers)	✓	✓	Mena et al. (2011); Gustavsson and Stage (2011); Calvo-Porral et al. (2017); Muth et al. (2019); Spang et al. (2019); Cicatiello et al. (2020); dos Santos et al. (2020)
	Product sorted out due to industry's quality standards (e.g., weight, size, shape and appearance)	✓	✓	Mena et al. (2011); Buzby and Hyman (2012); Calvo-Porral et al. (2017); Cicatiello et al. (2017); Parmar et al. (2017); Bilska et al. (2018); de Hooge et al. (2018); Wunderlich and Martinez (2018); Spang et al. (2019); Horoś and Ruppenthal (2021); Silapeux et al. (2021)
	Sprouting and biological aging of fresh products	✓	✓	Mena et al. (2011); Buzby et al. (2015); dos Santos et al. (2020); Silapeux et al. (2021)
	Supply chain inefficiencies (e.g., lack of cooperation, coordination, trust and SC contracts)	✓		Francis et al. (2008); Buzby et al. (2015); Gokarn and Kuthambalayan (2017); Chen and Chen (2018); Kolawole et al. (2021)
	Unpurchased products	✓	✓	Buzby et al. (2015); Tesfay and Teferi (2017); Silapeux et al. (2021)
	Inadequate market systems	✓	✓	Munesue et al. (2015); Emana et al. (2017); Gokarn and Kuthambalayan (2017); Tesfay and Teferi (2017)
	Inefficient procurement channels	✓		Gokarn and Kuthambalayan (2017)
	Insufficient storage conditions	✓		dos Santos et al. (2020); Silapeux et al. (2021)
	Non-adherence to standard and procedures	✓		Kolawole et al. (2021)

1.4.5 Transport

The process of transporting food is investigated separately, because most authors agree that moving food and marketing food are two very distinct activities within FSCs and there is a dearth of studies investigating the generation of FLW during the transport of food products (Lipinska et al., 2019). This is fundamental to understand the causes of FLW occurring in-between the stages of FSCs.

During transport, FLW is greatly influenced by the type of transport, infrastructures, distance between pickup and delivery and duration of moving and handling (Martínez et al., 2014), particularly in the transport of live animals, where the quantity of bruises caused to carcasses is used as an indication of animal welfare (Nielsen et al., 2011; Mendonça et al., 2018). The product's quality deteriorates due to physical phenomena (shock, vibration, compression), chemical processes (oxidation, moisture transfer), biological processes (microbial contaminations); and direct losses occur due to mishandling and spillages (Marsh et al., 2001). Food products are also damaged (e.g., bumps and bruises) due to poorly maintained roads. Rainy seasons inhibit the use of rural road infrastructures because of landslides or road blockages. On the contrary, during dry seasons, dust can contaminate food products. If the transportations' distance and duration is too high, food products ripen to a degree that decreases their likelihood of being sold, which is mainly challenging in developing countries due to the congestion, bad weather and/or failures in transport and infrastructures (Martínez et al., 2014).

Table 1.7 lists the causes of FLW during transport for developed and developing countries and by plant-based or animal-based food products.

Five out of the eleven causes of FLW identified are common for developed and developing countries. All of them were experienced by developing countries and none is specific to developed ones. There are more causes of FLW experienced in developing countries than in developed ones during transport, evidencing the role that transport plays on the generation of FLW in these countries. In these, FLW is mainly related to the lack of infrastructures and control over the cold chain, leading to interruptions of the cold chain and to expired products during transit and indicating an urgent need to invest in infrastructures and to implement technology to monitor the supply chain. For developed countries, FLW is generated by inefficiencies during transportation that occur because the decisions regarding food routes and destinations are often not based on the remaining shelf life.

When it comes to the food products transported across FSCs, ten relate to plant-based and six to animal-based food products. Although most of the strategies identified in animal-based supply chains are common with the ones identified in plant-based ones, there is no clear evidence that the mitigation strategies during transport are independent of the food product, since many strategies, identified mainly in developing countries, were only identified for plant-based supply chains.

Instead, this could mean that the plant-based food products have probably been more intensively studied in the literature.

Table 1.7 – Causes of FLW during transport of food products.

	Causes	P	A	References	
Developing countries	Expired products in-transit (e.g., distance travelled, delays in shipping)	✓	✓	Mena et al. (2014); Tesfay and Teferi (2017); Tostivint et al. (2017); Dora et al. (2021); Silapeux et al. (2021)	**Developed Countries**
	Improper handling	✓	✓	Mena et al. (2011); Kuyu et al. (2019); Lipinska et al. (2019); Kolawole et al. (2021)	
	Inadequate packaging	✓		Buzby and Hyman (2012); Macheka et al. (2013); Priefer et al. (2016); Emana et al. (2017); Wohner et al. (2019)	
	Interruption of the cold chain	✓	✓	Mena et al. (2011); Mena et al. (2014); Priefer et al. (2016); Corrado et al. (2017); Salihoglu et al. (2018); Lipinska et al. (2019)	
	Lack of cold chain facilities	✓	✓	Mena et al. (2014); Priefer et al. (2016); Sibomana et al. (2016); Corrado et al. (2017); Gokarn and Kuthambalayan (2017)	
	Poor transportation infrastructures	✓	✓	Sibomana et al. (2016); Tesfay and Teferi (2017); Kolawole et al. (2021)	
	Inadequate transportation networks	✓		Macheka et al. (2013); Gardas et al. (2017); Gokarn and Kuthambalayan (2017); Kuyu et al. (2019)	
	Lack of refrigerated carriers/trucks	✓		Macheka et al. (2013); Balaji and Arshinder (2016); dos Santos et al. (2020); Dora et al. (2021)	
	Lack of traceability systems	✓		Balaji and Arshinder (2016); Gardas et al. (2017); Gokarn and Kuthambalayan (2017)	
	Over packing	✓		Kuyu et al. (2019); dos Santos et al. (2020)	
	Carcass trimmed and condemned for bruises		✓	Jaja et al. (2018)	

1.4.6 Discussion

Sixty-one different causes of FLW were collected from the literature, from which forty were reported in developed countries, forty in developing ones and seventeen were reported by both. For developed countries, the distribution stage exhibited the greater number of causes (19), which is in agreement with the idea that FLW in these countries is concentrated at the downstream stages of FSCs (Bräutigam et al., 2014; Balaji and Arshinder, 2016; Shafiee-Jood and Cai, 2016). However, the agricultural production stage also displayed a large number of causes (16). This is a reflection of the focus of the literature on the production and the distribution stages, often underestimating the other stages of FSCs. For developing countries, the agricultural production stage exhibited the greater number of causes (14), which is also in agreement with the idea that FLW in these countries occurs mainly in earlier stages of FSCs due to inefficient harvesting, storage, transport and processing (Verghese et al., 2015). From the sixty-one causes of FLW identified, forty-nine relate to plant and thirty to animal-based products, showing that there is a deeper understanding of the causes of FLW for the plant-based products. Twenty-nine causes of FLW are common to both plant and animal-based products, evidencing a lack of studies targeting animal-based products in particular, since the vast majority of the animal-related causes are common to plant-based products. The Table A provided in Appendix A shows that the plant-based products most studied are fruits and vegetables like tomato, banana, maize and potato, and some of the animal-based products studied are dairy products, fish, cattle and poultry.

The causes of FLW identified in this review have a managerial, infrastructural, behavioural or technological focus. Causes with a managerial focus (e.g., inadequate forecasting or product ordering, supply chain inefficiencies like lack of coordination, excess stock due to take-back agreements and orders' cancellations), a behavioural focus (e.g., improper handling, consumers' confusion regarding date labels), and a technological focus (e.g., equipment malfunctions, inadequate technologies for harvesting or lack of traceability systems) are frequently identified in both developed and developing countries. On the other hand, the causes with an infrastructural focus (e.g., poor transportation infrastructures or poor storage conditions and insufficient storage facilities) appear to be more recurrent in developing countries.

In sum, this literature review shows a need to further study the causes and the mitigation strategies of FLW for developing countries and especially for other products than fruits and vegetables (which are the food products more frequently studied), to better understand how FLW is generated in FSCs. It also suggests that the causes of FLW in FSCs vary with the level of economic development of a country, with the stages of FSCs and with the different food products, which in turn will also condition the selection and the design of mitigation strategies capable of reducing FLW along FSCs for different contexts.

Some causes from one stage of FSCs are dependent of decisions taken at other stages (e.g., agricultural production) and other causes are experienced in more than one stage (like products sorted out due to industry's quality standards or inadequate packaging and handling), leading to the conclusion that different causes along FSCs must be dependent on each other. Because of that, researchers have recently tried to go beyond the identification of the causes of FLW and have attempted to establish relationships and priorities between them. Different multi-criteria decision-making (MCDM) methods have been used to model the interrelationships between the causes of food loss and waste in the Brazilian beef supply chain (Magalhães et al., 2020) and of fruit and vegetable waste in India (Balaji and Arshinder, 2016; Gardas et al., 2017; Raut et al., 2018) and in Portugal (Magalhães et al., 2021). These analyses allowed the development of graphic models that depict the different levels of dependency for the causes under study, and to estimate their driving and dependence powers, thus determining which are the most influential for the system under analysis. In conclusion, merely identifying what is causing FLW is not enough to deal with the FLW problem. To help decision makers choose the most appropriate strategies to tackle FLW in a given context, it is necessary to study which causes are the most influential.

1.5. Mitigation Strategies of Food Loss and Waste

On a global scale, researchers and policy-makers are working to establish reduction strategies that address FLW at each stage of FSCs, by adopting a sustainable production and consumption approach and, more recently, leaning towards a circular economy approach (Principato et al., 2019; Al-Saidi et al., 2021; Velenturf et al., 2021; Velasco-Muñoz et al., 2021). The implementation of these strategies must be adapted to the specific region, with particular consideration for local infrastructures, energy, markets, and education. However, the definition and implementation of FLW mitigation strategies can be quite challenging, due to: inconsistencies in terminologies and the definitions of FLW used; lack of reliable and consistent data; lack of applied research; lack of information on socioeconomic impacts; the need to monitor and evaluate existing policies and the need for a holistic approach to address FLW (Vilariño et al, 2017). The latter is crucial to establish the most appropriate mitigation strategies, since many causes of FLW are transversal to different stages of FSCs. Therefore, this literature review investigated the mitigation strategies of FLW for the stages and processes of FSCs depicted in Figure 1.8, to keep a holistic understanding of this issue.

1.5.1 Agricultural Production

The strategies to mitigate FLW encountered in the literature for the agricultural production stage of FSCs are listed in Table 1.8. They are again divided by developed and developing countries and by plant-based or animal-based food products. The shaded mitigation strategies of FLW identify the ones that are common to both developed and developing countries.

In this stage, fifteen strategies were identified, from which five are recommended to be implemented in developed countries, seven in developing countries and three in both. Mitigation strategies like shortening the supply chain, selling directly to retailers or consumers (mainly to sell products sorted out due to industry's quality requirements), training staff to ensure an adequate product handling and improving coordination and information sharing between the members of FSCs should be implemented in both developed and developing countries. However, in developed countries, mitigation strategies are more linked to pursuing supply chain collaboration and information sharing, to enable collaborative forecasting, a better adjustment of safety stocks and a shift towards a make to order flow. While in developing countries, the mitigation strategies are more linked to improvements in the harvesting process (attention to ripening stage, harvesting during cool weather and improving packing methods). The needs between the two economic contexts are very distinct and in agreement with the causes of FLW identified for the different economic contexts. In developing countries, for example, the causes of FLW relate to the lack of infrastructures or technology implementation and to the lack of knowledge or training regarding the ideal time of harvesting or the ideal stage of maturity for harvesting.

Table 1.8 – Mitigation strategies of FLW in the Agricultural Production stage.

Countries	Mitigation Strategies	P	A	References
Developed Countries	New markets for sub-standard products (e.g., second hand food stores)	✓		Calvo-Porral et al. (2017); Plazzotta et al. (2017); Chen and Chen (2018)
Developed Countries	Optimisation of production and harvesting processes and infrastructures			Richter and Bokelmann (2016); Chen and Chen (2018)
Developed Countries	Adjust levels of safety stock	✓	✓	Bertolini et al. (2013b); Liljestrand (2017)
Developed Countries	Collaborative forecasting	✓	✓	Mena et al. (2011); Liljestrand (2017)
Developed Countries	Make to Order flows	✓	✓	Liljestrand (2017)
Developed Countries; Developing countries	Coordination and information sharing	✓	✓	Kaipia et al. (2013); Macheka et al. (2013); Munesue et al. (2015); Gadde and Amani (2016); Chen and Chen (2018); Kolawole et al. (2021)
Developed Countries; Developing countries	Training staff for better and safe product handling	✓	✓	Mena et al. (2011); Prusky (2011); Macheka et al. (2013); Munesue et al. (2015); Emana et al. (2017); Chen and Chen (2018)
Developed Countries; Developing countries	Shorten supply chains, to sell directly to retail/consumers	✓		Prusky (2011)
Developing countries	Attention to ripening stage	✓		Prusky (2011)
Developing countries	Decrease production when the refrigerators are full		✓	Tesfay and Teferi (2017)
Developing countries	Disinfestation and protection against re-infestations	✓		Prusky (2011)
Developing countries	Harvesting during cool weather	✓		Emana et al. (2017)
Developing countries	Keeping product in the shade/cool places	✓		Emana et al. (2017)
Developing countries	Improving field packing methods during harvesting	✓		Prusky (2011)
Developing countries	Organising small farmers, diversifying/upscaling their production/marketing			Munesue et al. (2015)

When it comes to the food products, there are twelve strategies that could be implemented in plant and six in animal-based supply chains. Besides showing a greater focus in plant-based products, Table 1.8 also shows that six strategies are common for both products, meaning that there is a gap in the literature regarding the study of mitigation strategies to be applied in animal-based products, especially for developing countries, where the majority of recommended mitigation strategies are specific to plant-based products.

1.5.2 Post-harvest Handling and Storage

The strategies to mitigate FLW encountered in the literature for the post-harvest handling and storage stage of FSCs are listed in Table 1.9 and are divided by developed and developing countries and by plant-based or animal-based food products.

Table 1.9 – Mitigation strategies of FLW in the Post-harvest Handling and Storage stage.

	Mitigation Strategies	P	A	References	
	Post-harvest (processing and packaging) technologies to increase product shelf life	✓	✓	Antunes et al. (2007); Mena et al. (2011); Mercier et al. (2017)	Dev. Countries
Developing countries	Training staff for better and safe product handling	✓	✓	Mena et al. (2011); Prusky (2011); Macheka et al. (2013); Munesue et al. (2015); Emana et al. (2017); Chen and Chen (2018)	Dev. Countries
Developing countries	Maintaining regularly the cold storage facilities		✓	Tesfay and Teferi (2017)	
Developing countries	Investment in infrastructure and cold chain facilities			Munesue et al. (2015)	
Developing countries	Develop containers to better protect produce from damage	✓		Prusky (2011)	
Developing countries	Improvement of cooling methods	✓		Prusky (2011); Emana et al. (2017)	

There is a noticeable decrease of mitigation strategies from the previous stage to this one. For the post-harvest handling and storage stage, six mitigation strategies were identified, from which one should be implemented in developed countries, four in developing ones and one in common.

In developed countries, besides training staff for better product handling (which is a strategy that developed countries should apply too); the only other strategy identified is to improve post-harvest techniques capable to increase product shelf life. In developing countries, the strategies are mainly related to the maintenance of the cold chain, since FLW occurs mainly due to insufficient infrastructures and bad sanitisation that leads to contaminations and interruptions of the cold chain. From a general point of view, and contrary to the conclusions from the previous stage of FSCs, where the strategies for developed countries were more of a managerial nature, here the solutions for both levels of economic development are linked to technological improvements.

There are four strategies that should be implemented in plant and three in animal-based supply chains. From these, two are common to both products and the solutions are only disparate for developing countries, where solutions for plant-based products are related to developing containers to prevent mechanical damages and improve cooling methods to prevent quality deterioration, while for animal-based products the cold storage facilities must be regularly maintained to prevent interruptions of the cold chain.

1.5.3 Processing and Packaging

Table 1.10 lists the strategies to mitigate FLW encountered in the literature for the processing and packaging stage of FSCs, divided by developed and developing countries and by plant-based or animal-based food products.

Table 1.10 – Mitigation strategies of FLW in the Processing and Packaging stage.

Mitigation Strategies	P	A	References	Countries
Post-harvest (processing and packaging) technologies to increase product shelf life	✓	✓	Antunes et al. (2007); Mena et al. (2011); Mercier et al. (2017)	Developed Countries
Adjustment of packaging size			Richter and Bokelmann (2016); Chen and Chen (2018)	Developed Countries
Correct date marking			Verghese et al. (2015)	Developed Countries
Markets for sub-standard products			Munesue et al. (2015)	Developed Countries
Improve traceability (e.g., intelligent packaging with RFID tags, blockchain technology)	✓		Wang et al. (2010); Giuseppe et al. (2014); Verghese et al. (2015); Gautam et al. (2017)	Developed Countries
Develop new products from sub-optimal food		✓	Abualtaher and Bar (2020)	Developed Countries
Coordination and information sharing	✓	✓	Kaipia et al. (2013); Macheka et al. (2013); Gadde and Amani (2016); Chen and Chen (2018); Kolawole et al. (2021)	Developed and Developing Countries
Training staff for better and safe product handling	✓		Prusky (2011); Munesue et al. (2015); Emana et al. (2017)	Developing Countries
Develop containers to better protect produce from damage	✓		Prusky (2011)	Developing Countries
Improvement of cooling methods	✓		Prusky (2011); Emana et al. (2017)	Developing Countries

The literature identifies ten mitigation strategies to reduce FLW in the processing and packaging stage, six to be implemented by developed countries, three by developing countries and one by both. The strategies in developed countries are more related to smaller technological improvements to help increase the products shelf life and improve traceability. In developing countries, on the other hand, the strategies are more related to improvements of the process (cooling methods) and of the product handling (training staff and develop containers). The only strategy that should be applied by developed and developing countries is the improvement of the coordination and information sharing between the members of FSCs. It is interesting to note that damaged packaging was one of the causes of FLW referred previously in developed and developing countries for the processing and packaging stage of FSCs, but Table 1.10 shows that developing new or more suitable packaging was not identified as a mitigation strategy in this stage. Even though this is just an example, many more can be used along the stages of FSCs, showing that there is an absence in the literature in bridging the knowledge regarding the causes of FLW with the definition and the design of mitigation strategies capable of tackling those causes.

When it comes to the food products, six mitigation strategies relate to plant-based supply chains and three relate to animal-based supply chains. This is a bit off-balanced, since the majority of the causes of FLW identified previously for this stage are common to both types of products. This indicates a clear focus on plant-based products in this stage and a lack of studies trying to comprehend how FLW can be reduced for animal-based products. There is not enough data to conclude whether or not the strategies in this stage are specific to the type of product.

1.5.4 Distribution

The strategies to mitigate FLW encountered in the literature for the distribution stage of FSCs are listed in Table 1.11 and are divided by developed and developing countries and by plant-based or animal-based food products.

Table 1.11 – Mitigation strategies of FLW in the Distribution stage.

Mitigation Strategies	P	A	References	
New markets for sub-standard products (e.g., second hand food stores)	✓		Calvo-Porral et al. (2017); Plazzotta et al. (2017); Chen and Chen (2018)	**Developed Countries**
Decrease the wholesale pack size		✓	Eriksson et al., 2014	
Adjust levels of safety stock	✓	✓	Bertolini et al. (2013b); Liljestrand (2017)	
Collaborative forecasting	✓	✓	Mena et al. (2011); Liljestrand (2017); Cicatiello et al. (2020)	
Improve forecasting accuracy measures	✓	✓	Christensen et al. (2021)	
Make to Order flows	✓	✓	Liljestrand (2017)	
Post-harvest (processing and packaging) technologies to increase product shelf life	✓	✓	Antunes et al. (2007); Mena et al. (2011); Mercier et al. (2017)	
Correct date marking			Verghese et al. (2015)	
Adjust availability during promotions	✓	✓	Mena et al. (2011)	
Improve traceability (e.g., intelligent packaging with RFID tags, blockchain technology)	✓		Wang et al. (2010); Bertolini et al. (2013a); Bertolini et al. (2013b); Giuseppe et al. (2014); Verghese et al. (2015); Gautam et al. (2017)	
Central ordering system allowing changes by store to reflect local events	✓	✓	Mena et al. (2011); Horoś and Ruppenthal (2021)	
Clear promotional planning process	✓	✓	Mena et al. (2011)	
Conduct regular FLW audits and set reduction targets			Chen and Chen (2018)	
Continuous replenishment systems linked to sales for products with stable demands	✓	✓	Mena et al. (2011)	
Cooperation between FSC stakeholders		✓	Kaipia et al. (2013); Gadde and Amani (2016)	
Development of new packaging	✓	✓	Mena et al. (2011); Liljestrand (2017); Porat et al. (2018)	
Developing new or processing products likely to be wasted			Calvo-Porral et al. (2017)	
First-in-first-out or first-expired-first-out stock rotation in store	✓	✓	Mena et al. (2011); Jedermann et al. (2014)	
Food products assortment at store			Calvo-Porral et al. (2017)	
Help from IT to manage stock and promotions	✓	✓	Mena et al. (2011)	
Implementing RFID technology to improve availability of products in store	✓	✓	Bertolini et al. (2013b)	

	Measures of service level (prioritizing the costs of FLW)	✓	✓	Liljestrand (2017)
	Movement among stores to balance inventory for short-life products	✓	✓	Mena et al. (2011)
	Price reductions near end of expiration date	✓	✓	Liljestrand (2017); Cicatiello et al. (2020); Horoś and Ruppenthal (2021)
	Regular adjustment of the variety of products in store			Newsome et al. (2014); Cicatiello et al. (2020)
	Regular checks of refrigeration equipment	✓	✓	Mena et al. (2011); Cicatiello et al. (2020)
	Regular stock/inventory control			Richter and Bokelmann (2016)
	Reliable storage and in-store displays	✓	✓	Mena et al. (2011)
	Revised food product standards (e.g., promote ugly food movements)	✓		Richter and Bokelmann (2016); van Giesen and de Hooge (2019)
	Support local productions to shorten lead times	✓	✓	Mena et al. (2011)
	Vertical integration to shorten lead times	✓	✓	Mena et al. (2011)
	Visualising damaged packaging	✓	✓	Liljestrand (2017)
Developing Countries	Coordination and information sharing	✓	✓	Kaipia et al. (2013); Macheka et al. (2013); Gadde and Amani (2016); Chen and Chen (2018); Kolawole et al. (2021)
	Training staff for better and safe product handling	✓	✓	Mena et al. (2011); Macheka et al. (2013); Chen and Chen (2018); Cicatiello et al. (2020); dos Santos et al. (2020); Horoś and Ruppenthal (2021)
	Food redistribution (e.g., food banks)	✓		Calvo-Porral et al. (2017); dos Santos et al. (2020); Horoś and Ruppenthal (2021)
	Marketing cooperatives and improved market facilities			Munesue et al. (2015); dos Santos et al. (2020)
	Improve storage facilities	✓		dos Santos et al. (2020)

In the distribution stage, the literature refers thirty-seven mitigation strategies to reduce FLW in developed countries, while only two was encountered for developing countries and three for both. This is plausible, since there were more causes experienced in developed countries than in developing ones. In developing countries, the mitigation strategy identified is in line with the causes at this stage. Marketing cooperatives and improved market facilities should be developed to cope with the inadequate market system and the inefficient procurement channels (see section 1.4.4). Even for developed countries, the identified mitigation strategies are very linked to the causes of FLW experienced. The clear focus of the literature on the distribution stage lead to a better understanding of the causes of FLW and the consequent mitigation strategies at this stage than for other stages of FSCs, particularly in developed countries. The concentration of studies can be explained by the fact that FLW in developed countries occurs mainly at the downstream stages of FSCs, as said before. However, this highlights how much neglected have been the other stages of FSCs in detriment of the distribution stage.

Regarding the food products, the focus of the literature seems to be well adjusted in this stage between plant and animal-based products and the fact that twenty-three of these solutions are common for both products, leads to the conclusion that the mitigation strategies in the distribution stage are independent of the food products.

1.5.5 Transport

Table 1.12 lists the mitigation strategies of FLW for the transport of food products, for developed and developing countries and by plant-based or animal-based food products.

Table 1.12 – Mitigation strategies of FLW relating to the transport of food products.

	Mitigation Strategies	P	A	References
Developed Countries	Improve traceability (e.g., intelligent packaging with RFID tags, blockchain technology)	✓		Wang et al. (2010); Giuseppe et al. (2014); Haass et al. (2015); Mejjaouli and Babiceanu (2015); Rossaint and Kreyenschmidt (2015); Verghese et al. (2015); Gautam et al. (2017)
Developed Countries	Dynamic Shelf Life based management		✓	Giuseppe et al. (2014); Buisman et al. (2019)
Developed Countries	Investment in transportation/infrastructures	✓		Nourbakhsh et al. (2016)
Developed Countries	Investment in logistics (route optimisation, taking into account the condition of roads)		✓	Lipinska et al. (2019)
Developing Countries	Training staff for better and safe product handling	✓		Prusky (2011); Munesue et al. (2015); Emana et al. (2017)
Developing Countries	Improvement of cooling methods	✓		Prusky (2011); Emana et al. (2017)
Developing Countries	Increasing transport by refrigerated trucks	✓		Prusky (2011)
Developing Countries	Packaging development	✓		Emana et al. (2017)
Developing Countries	Decreasing delays in deliveries		✓	Tesfay and Teferi (2017)

For the process of transporting food across FSCs, the literature refers nine mitigation strategies to reduce FLW, four mitigation strategies to be implemented in developed countries and five in developing countries. It is interesting to note that there were no causes specific to developed countries (see section 1.4.5). All five causes experienced in developed countries were experienced in developing countries also. Therefore, the fact that the literature mentions four mitigation strategies to be applied only in developed countries, suggests that the same causes of FLW should be tackled differently for countries with different levels of economic development. At this stage, also seems to be a misconnection between the causes and the strategies identified. No cause of FLW experienced in developed countries referred a lack of infrastructures; however investing in infrastructures is pointed as a solution to reduce FLW in-transit.

From the nine strategies identified, six relate to plant-based food products and three to animal-based products. Table 1.12 shows that no solution is common to both products, leading to the conclusion that, unlike in the distribution stage, the food product being transported has influence over the mitigation strategies to implement.

1.5.6 Discussion

In sum, as for the causes of FLW, there are several mitigation strategies with a managerial, infrastructural, behavioural or technological focus. Strategies with a managerial focus are mainly associated to developed countries, with the need to: develop new markets and new ways to sell or redistribute sub-standard products, improve in-store management, or even improve the management of the supply chain (e.g., coordination and information sharing between stakeholders). The strategies more transversal to all FSC stages and that seem to be more successful to combat FLW in FSCs have a managerial focus and relate to collaboration (Mercier et al., 2017; Bustos and Moors, 2018), cooperation (Göbel et al., 2015), and coordination (Kouwenhoven et al., 2012; Tesfay and Teferi, 2017) between stakeholders. These can improve the organisation of FSCs and the visibility of information along the stages, increasing forecast accuracy and improving the organisation of promotions (Mena et al., 2011), minimise the gaps and fluctuations between supply and demand and make the stakeholders more competitive and productive (Balaji and Arshinder, 2016). In addition, improving communication between the stakeholders reduces uncertainty and improves responsiveness to supply chain disruptions, helping to reduce costs and FLW along FSCs (Kaipia et al., 2013). Managerial decisions regarding the improvement of the forecast accuracy also shows promising results to mitigate FLW. Christensen et al. (2021) studied a new forecasting accuracy measure that incorporates the shelf-life of the product and the levels of freshness and of waste, concluding that this new measure assured increased freshness of the food product and reduced levels of FLW, without compromising product availability, when compared to existing forecasting accuracy measures.

Mitigation strategies with an infrastructural focus are mainly linked to developing countries that need to: invest and develop infrastructures (e.g., roads, cold chain facilities and refrigerated trucks) and develop new technologies and methods (e.g., improve packing methods during harvesting, improve maintenance of cold storage facilities and develop new containers and new packaging). Strategies with a behavioural and a technological focus should be implemented by both developed and developing countries. Both should train staff to ensure a proper product handling, although developing countries need to go a bit further and spread good practices to promote better habits during harvesting, handling and storage (like harvesting during cool weather or improving cooling methods by keeping products in shaded places). Regarding the technological strategies, the ones to be implemented in developing countries are more related to the maintenance of the integrity of the cold chain, while in developed countries these strategies are more related to the implementation of existing or new technologies (e.g., RFID, TTIs and blockchain technology [Zhao et al., 2019]). For instance, automated Programmable Logic Controllers (PLCs) decrease manual errors and process failures, while enabling firm-level monitoring of a range of process parameters, and Enterprise Resource Planning (ERP) can help to identify efficient routing systems, improving logistics networks. These technologies can help to reduce FLW along integrated FSCs by enhancing operational visibility and process control (Chauhan, 2020). However, the implementation and the good use of these technologies is dependent on the information sharing between all members of FSCs and on their level of cooperation and collaboration. This comes to show how interlinked these mitigations strategies are and how there is not a single answer on how to mitigate FLW along FSCs.

Overall, there are more mitigation strategies referred in the literature for developed countries and considerably fewer for developing ones, showing a focus in the literature towards developed countries. Perhaps this focus in developed countries is not intentional and only a reflexion of the complexity of the issue in these countries. FLW is highly influenced by managerial decisions regarding promotions, routing or collaboration along FSCs, whose solutions are not obvious or unique for all FSC actors, which may lead to a wider range of mitigation strategies. On the other hand, the number of strategies may be explained by the fact that basic and obvious solutions to FLW were already applied and the efficiency gains achieved with the mitigation strategies are smaller. In developing countries, the solutions are more straightforward, regarding the improvement of infrastructures and good practices to maintain the cold chain, so fewer mitigation strategies are needed to combat FLW. These countries need to solve the basic issues first, before thinking about high-technology solutions like quality monitoring through RFID tags or route optimisation. These solutions are not relevant unless there is an effective transport network or access to refrigerated warehouses, for example.

This review also highlights a focus on plant-based rather than on animal-based products. Regarding the stages of FSCs, there is a clear focus on the distribution stage, when compared to the other stages of FSCs, mainly due to the focus of studies on developed countries. The fact that most efforts to fight FLW in developing countries are focused on the agricultural production and post-harvest handling and storage stages corroborates the literature, emphasising that FLW is a more significant problem at the earlier stages of FSCs in developing countries. The same happens for developed countries, where the literature review highlights that most mitigation strategies relate to the distribution stage, corroborating the literature-borne idea that FLW occurs mainly at the downstream stages of FSCs for developed countries. The biggest concern after distribution seems to be the agricultural production stage, which is in agreement with the analysis of the causes of FLW. Section 1 clearly indicates that some problems observed in agricultural production are related to retail, mainly due to overproduction deriving from supply agreements with retail, to the inadequacy of the forecasting of demand or product ordering or to the standards imposed by retail regarding weight, size, shape and appearance. This leads to the conclusion that the implementation of mitigation strategies must be guided by the identification of the causes of FLW in a specific context. However, there is a dearth of studies connecting mitigation strategies to specific causes of FLW, evidencing an absence in the literature in bridging the knowledge regarding the causes of FLW with the definition and design of mitigation strategies capable of coping with those causes.

Despite the extensive knowledge on the causes of FLW and consequent mitigation strategies in the distribution stage, this literature review shows a lack of understanding for the other stages of FSCs, which have been less studied in the literature. Then again, perhaps this merely reflects the fact that the solutions for the causes of the other stages of FSCs are not as evident as in distribution. This review also shows that there are far more studies concerned with the identification of the causes of FLW, than with proposing efficient mitigation strategies, even though the total number of mitigation strategies found (73 strategies) is close to the total causes identified (80 causes). Regarding the food products analysed, the different stages of FSCs show that the mitigation strategies are dependent on the food product, with the exception of the distribution stage were almost all strategies identified are common to both type of products. Therefore, the implementation of mitigation strategies should be guided by the identification of the causes of FLW, due to the discrepancies in needs evidenced by the two different economic contexts, the stages of FSCs and the different food products. However, the majority of the literature is either focused on the causes of FLW or on the mitigation strategies to reduce FLW and no study has yet linked specific causes of FLW to specific strategies to be implemented.

1.6. Opportunities for Future Research

This literature review exposed that there are still many opportunities for future research to close the gaps in the existing knowledge and fully understand the causes of FLW and the mitigations strategies practitioners should implement to combat FLW within their businesses.

Future studies should investigate the upstream stages of FSCs for developed countries and downstream stages for developing ones, since these have been broadly overlooked in the literature (Xue et al., 2017; Wunderlich and Martinez, 2018), to contextualize the extent of FLW in these parts of FSCs. When it comes to the causes of FLW, more investigations are needed for countries with different levels of economic development and for different food products to fully understand how the causes of FLW influence each other and to identify the root causes of FLW that ultimately influence the generation of FLW. MCDM methods, like Interpretive Structural Modelling (ISM) (e.g., Gardas et al., 2017; Magalhães et al., 2020; Magalhães et al., 2021) and Analytic Hierarchy Process (AHP) (e.g., Raut et al., 2018), have showed potential to assess the interrelatedness between the causes of FLW and to prioritise them according to their relative importance, in order to identify the ones more critical to be mitigated.

This review evidenced a need to investigate to which extent FLW is preventable and where FLW mitigation strategies can be implemented in the food lifecycle (Buzby and Hyman, 2012; Jeswani et al., 2021). Further research connecting mitigation strategies to the stages of FSCs where the causes of FLW take place, and to the specific causes they help mitigating, are also needed. Interdisciplinary research is fundamental to understand how improvements in supply chain management and technology implementation can reduce FLW (Hodges et al., 2011; Shafiee-Jood and Cai, 2016). Another important avenue for future work is to evaluate how effective the mitigation strategies are in reducing FLW (Tromp et al., 2016; Vilariño et al, 2017; Xue et al., 2017) and to what extent the mitigation strategies complement one another. MCDM methods, like the Weighted Aggregated Sum Product Assessment (WASPAS), has shown potential to compare different solutions (e.g., Prajapati et al., 2019). Researchers should also investigate on what criteria the selection of mitigation strategies should be based on to help decision makers choose the most appropriate strategies to reduce FLW in their particular circumstances, since the different mitigation strategies may need different key performance indicators to properly be evaluated due to their specificities.

Considering that the selection of the most appropriate mitigations strategies to implement are reliant on the causes of FLW manifesting in a particular scenario, future studies should also investigate how the knowledge on the interdependencies amongst the causes of FLW, and on the root causes of FLW in specific scenarios, can be incorporated as criteria in the selection process of the mitigation strategies. Future work should also investigate what implications the adoption of mitigation strategies will have on the redesign of FSCs in the long run, which can be tested by discrete event simulation (e.g., Leithner and Fikar, 2019).

1.7. Framework Development to Investigate Food Loss and Waste in the Future

A research framework was developed in this paper to address the gaps encountered in the literature and to guide future investigations seeking to mitigate FLW along FSCs. The developed framework is presented in Figure 1.9 and comprises 8 steps that are essential to mitigate FLW in FSCs:

1. Carefully set the system boundaries and define the context of the problem, by establishing the scale (e.g., country, region), the time period (e.g., a year), the members of the FSC under study (e.g., one stage or the whole FSC), the food product, the goals (e.g., percentage of reduction of FLW) and strategies (i.e., position of each player regarding the reduction of FLW), since the paradigm of the FLW is different for countries with different levels of economic development, for different stages of FSCs, and for different food products;

2. Fully explain what is being considered as FLW to facilitate the validation and the comparability of the studies, since the methodologies used for FLW quantification are dependant of the FLW definition. Define the terminology to use and what will be considered FLW (e.g., only the avoidable part of food or only the edible part of food);

3. Define the units of measure (e.g., mass, economic value); identify the FLW flows and the FLW hotspots, by understanding how much of the initial food products reaches the different stages of the FSC under study; and, establish the methodologies for FLW quantification, since the FLW data is dependent on the stage of the FSC and on the units of measurement (e.g., physical weight or percentages). This would further enable the comparison of existing data across countries, commodities, and FSCs, which would further help explore patterns and driving factors of FLW generation;

4. Identify the causes of FLW along the FSC under study, gathering information both from literature and from the knowledge of the industry's and academia's experts;

5. Study the relationships between the identified causes of FLW using a fitting MCDM method to identify which are indeed the root causes of FLW, since these will influence the strategies more urgent to put in place to mitigate FLW.

6. Identify potential mitigation strategies to be applied along the FSC under study to tackle the root causes of FLW identified previously and define appropriate evaluation criteria to assess the performance of the mitigation strategies.

7. Rank the mitigation strategies according to their performance on the set of evaluation criteria selected, using a fitting MCDM method, to determine the strategies with greater potential to reduce FLW along the FSC under study.

8. Investigate the impact that the implementation of the mitigation strategies will have on the FSC under study and identify redesign strategies for the FSC, if necessary. Lastly, assess the performance of the FSC and the efficiency of the mitigation strategies to reduce the levels of FLW along the FSC, through simulation, to establish if the goals set at the beginning were accomplished.

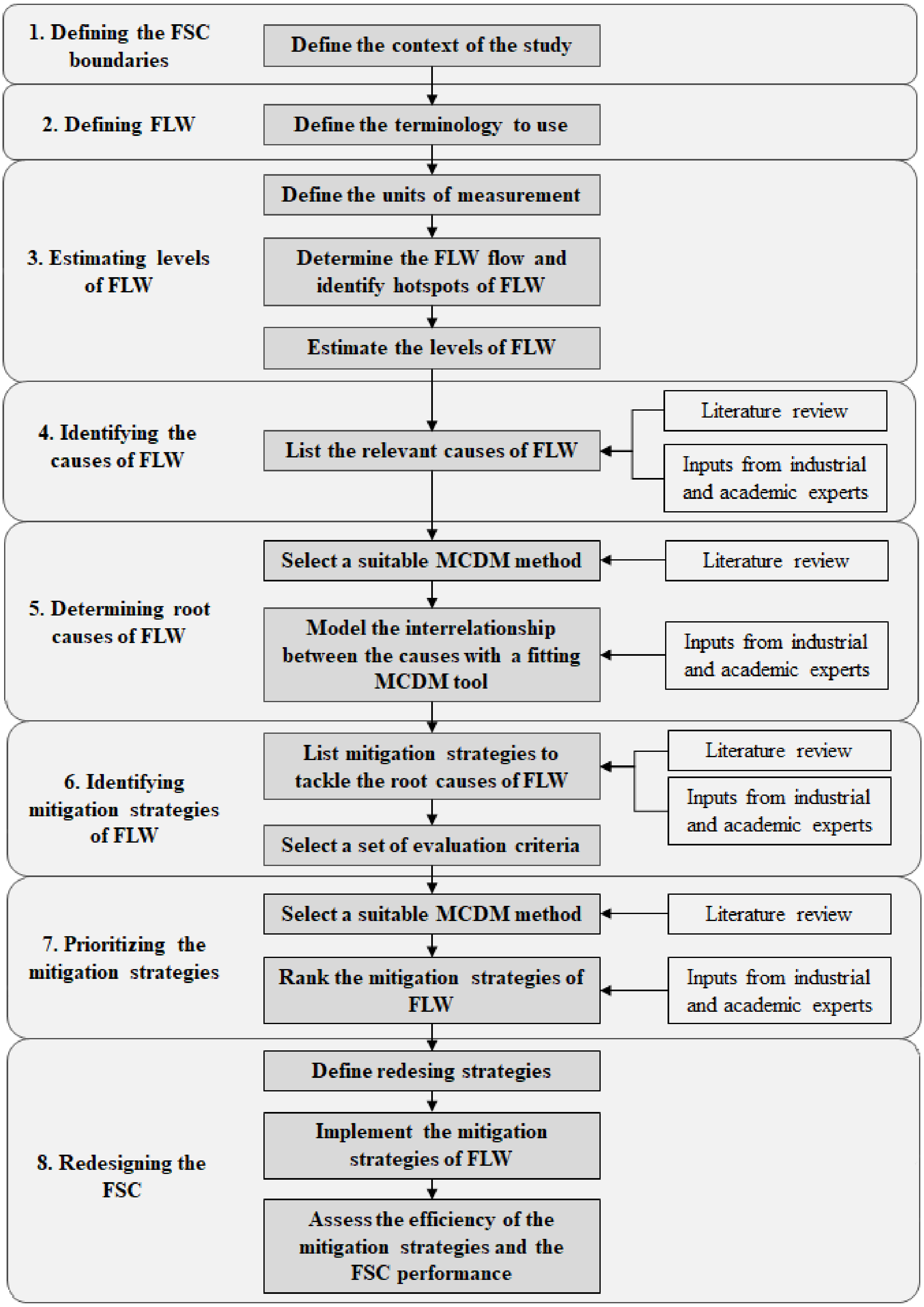

Figure 1.9 – Framework to reduce FLW along FSCs.

1.8. Conclusions

This paper presents a systematic literature review that consistently summarises the causes and the mitigation strategies of FLW, highlighting the differences encountered between countries with different levels of economic development, for the different stages of FSCs and for different food products. It is also the first of its kind to investigate the transport of food products along FSCs to assess what happens in-between the stages of FSCs.

RQ1 was answered by summarising the main causes of FLW from agricultural production to distribution in Tables 1.3 to 1.7. The majority of the causes are dependent on the stage of FSCs, on the food product and differ between developed and developing countries. Indeed, in developing countries, FLW occurs essentially at the earlier stages of FSCs, due to the lack of infrastructures and associated technical and managerial skills in food production and post-harvest processing. In developed countries, FLW arises mostly at the downstream stages, due to a lack of coordination and communication between different actors of FSCs and to the consumers' behaviour. At the in-between stages, both developed and developing countries deal with similar issues, there are problems with the time in-transit and with interruptions of the cold chain that compromise the quality of the food products. However, besides these common problems, developing countries still face basic issues regarding the lack and inadequacy of their infrastructures. All this implies that future studies need to maintain a holistic perspective to fully grasp what is happening at the different stages of FSCs and in-between them. Studies that determine the root causes of FLW and assess their interdependencies are also needed to fully comprehend how the causes of FLW influence each other and ultimately influence the generation of FLW, for different food products. It is also important to evaluate how each cause contributes to the generation of FLW, to be able to prioritise them according to their importance and identify the ones more critical to be mitigated.

Regarding RQ2, Table 1.8 to 1.12 were compiled to answer it. For developed countries, reducing FLW seems to be mainly linked to implementing technologies, developing new markets and new ways to sell or redistribute sub-standard products, improving in-store management and improving the supply chain management (e.g., coordination and information sharing between stakeholders). Developing countries; however, need to improve their infrastructures and disseminate good practices between stakeholders to reduce FLW across FSCs. Future studies should investigate the extent to which FLW is preventable, where FLW mitigation strategies can be implemented in the food lifecycle and evaluate how effective these strategies are, by estimating the trade-off between the necessary investment and the FLW reduction potential. It should also be investigated how the mitigation strategies complement one another and what criteria should their selection be based on, to help decision makers choose the most appropriate strategies to reduce FLW in their particular circumstances. Future research should also investigate how the knowledge on the interdependencies amongst the causes of FLW, and on the root causes of FLW in specific scenarios, can guide the selection of the most appropriate mitigation strategies and what implications the adoption of these strategies will have on the design of FSCs.

The main findings reported and the opportunities for future research highlighted in this review also enabled the development of a research framework to guide future investigations concerning the reduction of FLW in FSCs.

This literature review has mainly two limitations regarding the article selection process. First, the criteria used to select the articles might have excluded relevant studies from this review. Future SLRs can analyse conference proceedings, book chapters and even articles publish in other languages than English. Second, the keywords and strings used to search the databases also represent a limitation of this review, as they were based on published research and on the authors' assessment, and could be a source of bias, since the use of other keywords might have led to a different set of articles to analyse. Third, the authors only included articles available in WoS and Scopus databases. Future SLRs could improve their article selection process by searching for studies available in other academic databases.

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PART II – EMPIRICAL ANALYSIS

The second part of the thesis aims to provide empirical evidence of the suitability and the validity of the framework developed in Part I to guide the way towards the identification of the most promising mitigation strategies to reduce food loss and waste along food supply chains.

Chapter 2 analyses the relationships between the causes of food loss and waste in the Portuguese fruit and vegetable supply chain, identifying the root causes in this context and Chapter 3 analyses the relationships between the causes of food loss and waste in the Brazilian beef supply chain, identifying the root causes of food loss and waste in this context. Besides its contributions to the literature on the field as independent works, chapters 3 and 4 help to validate the steps of the framework developed in Part I for any geographical context and for any fresh food product. Moreover, Chapter 2 ensures the necessary background information for the analysis performed in Chapter 4. Chapter 4 uses the causes identified in the Portuguese fruit and vegetable supply chain to identify potential mitigation strategies to tackle them and reduce FLW along the supply chain. Afterwards, the identified strategies are ranked according to their performance under a set of evaluation criteria and the most promising mitigation strategies are prioritised for this context in particular. Besides this chapter's contribution to the field as an independent work, it helped to understand the suitability of the framework developed in Part I to successfully identify promising strategies to reduce FLW along the studied supply chain.

Chapter 2

Using a methodological approach to model causes of food loss and waste in fruit and vegetable supply chains[1]

Abstract

Food loss and waste occur at all stages of the food supply chain. Since their causes are interconnected and may influence each other, then approaches with holistic supply chain perspectives are useful to map their relationships and guide the selection, design and implementation of the appropriate mitigation strategies. In this paper, 14 causes of food loss and waste in fruit and vegetable supply chains were identified and divided into seven levels of influence, by the Interpretive Structural Modelling methodology, showing that the logistic related causes have a major influence on the others. Furthermore, five root causes were identified by the Matrix Impact of Cross Multiplication Applied to Classification analysis (inadequate transportation systems, inadequate or defective packaging, lack of storage facilities, poor handling and operational performance and lack of coordination and information sharing) and used to discuss the mitigation strategies that should be implemented to reduce food loss and waste.

Keywords: Interpretive Structural Modelling; root causes of FLW; mitigation strategies.

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2.1. Introduction

Food production is expected to increase 70% to meet the worldwide food supply needs by 2050 (Arivazhagan et al., 2016). However, one third, approximately 1.3 billion tonnes, of the total produced food to be consumed is still lost or wasted each year, thus wasting the 0.9 million hectares of land and 306 cubic kilometres of water needed for its production (Priefer et al., 2016). Food loss and waste (FLW) seems to represent not only a misuse of natural resources, but also a missed opportunity to feed the world's growing population. In this paper, FLW will refer to all the food discarded along the food supply chain (FSC), from agricultural production until retail.

Food products can deteriorate and be discarded at all stages of FSCs, while they are transported, cooled, processed, traded, treated and packaged. So, an analysis focusing on the different FSC stages is necessary to fully understand why food products are being discarded and what can be done to prevent this (Martínez et al., 2014). Although the prevention of FLW has been gaining attention in recent years and is now part of the political agenda (e.g. the European Commission has a commitment to halve FLW by 2030), the pattern and range of FLW along FSCs is still not completely known (Bräutigam et al., 2014; Magalhães et al., 2019). Its drivers must be identified to design and implement effective measures to prevent FLW (FUSIONS, 2016; Priefer et al., 2016). Hence, the identification of the different causes of FLW should be the first step to establish those strategies and to identify where and how they need to be applied (Priefer et al., 2016).

The causes of FLW are diverse and vary according to FSCs stages, the regions under study (Martínez et al., 2014; Bräutigam et al., 2014; Magalhães et al., 2019), and the food product under analysis (Arivazhagan et al., 2016). For instance, in Europe, fruits and vegetables are the most wasted food products, representing 54% of total FLW (Bräutigam et al., 2014). The fact that the causes of FLW are not independent from each other (Mena et al., 2011) also increases the difficulty in combating FLW. Although some researchers have studied the drivers of FLW (e.g. Thyberg and Tonjes, 2016; Canali et al., 2017), there is a lack of understanding of which causes are more influential concerning FLW and how they are related. Additionally, these studies also fail to elaborate on the most suitable mitigation strategies to be implemented to prevent FLW. Moreover, the research is noticeably more focused on the downstream FSC stages, particularly in the supplier and retailer interface (e.g. Mena et al., 2011) and on the consumer stage (Özbük and Coşkun, 2019), and the results are often hard to generalise (e.g. Arivazhagan et al., 2016; Emana et al., 2017). This paper attempts to address these shortcomings by studying the interactions between the causes of FLW within fruit and vegetable supply chains (FVSC). The research question guiding this paper is:

(RQ): How are the causes of food loss and waste along fruit and vegetable supply chains interrelated?

To address this question, a focus group, comprised by academics and experts from companies operating in Portugal with a considerable experience in producing, distributing and selling fruits and vegetables, was set up. Feedback from agricultural production to the retail stage of the FVSC was collected to maintain a supply chain perspective and reach a holistic understanding of the issue. The consumer stage was not considered, because the causes of FLW (at this stage) are related to consumers' behaviours and attitudes (Canali et al., 2017; Abdelradi, 2018), and there is already an extensive body of literature examining these: psychological, social, situational, demographic and socioeconomic factors of FLW (e.g. Aschemann-Witzel et al., 2015; Stancu et al., 2016; Schanes et al., 2018). Furthermore, the main challenges faced by practitioners from the other stages of FSCs have been overlooked and have received scant attention (Özbük and Coşkun, 2019). Therefore, the focus of this paper is to assess the causes of FLW that are related to the food products' flow along FVSCs and to the stakeholders' handling and decision-making from agricultural production to retail. The group of experts was carefully chosen to help with the selection of the relevant causes of FLW in FVSCs and to develop the Interpretive Structural Modelling (ISM) based model to represent the interrelationships between them. ISM was used due to its ability to capture dynamic complexities, when compared to other multi-criteria decision-making approaches (Shahabadkar et al., 2012), and because it is a qualitative tool with great potential to determine the structure of any system with distinguishable variables (Lim et al., 2017). Its results were complemented with a Matrix Impact of Cross Multiplication Applied to Classification (MICMAC) analysis to determine the causes' dependence and driver powers and identify the root causes of FLW. To conclude, a set of mitigation strategies were retrieved from the literature to identify the most suitable strategies to cope with the root causes of FLW in FVSCs. As far as we know, this is the first paper to use the results from integrated ISM and MICMAC methodologies to discuss which mitigation strategies should be implemented by practitioners to prevent FLW.

Portugal is a small food market, especially when compared to other European countries. Still, the grocery retail sales totalled 19.7 billion euros in 2017. These sales are predicted to grow 2.9% on average a year until 2022, outstripping the sales growth of 2.2% in Europe as a whole (Sonae, 2018). When it comes to Portugal's retail landscape, the market has essentially eight major players, whose aggregate market share has strengthened from 52% in 2007 to 77% in 2017 (Sonae, 2018). In the food industry, retailers exercise vertical control through contracts and the producers are obliged to make certain investments to sign those contracts (Monteiro and Caswell, 2009), evidencing the pressure that retailers exert in the whole supply chain, which will be relevant to the interpretation of the results. Further evidence of the importance that retail plays in

Portugal is the aggressiveness of the country's promotions management. In 2018, almost half of Portugal's retail sales were discounted and promotional items, making Portugal the fourth country in Europe registering the greatest number of sales of cut-price articles (Nielsen, 2019). 46% of all sales of domestic retail goods bought in Portugal had discounts, greatly exceeding the European average (29%). Regarding the country's contribution towards FLW, around 17% of the edible parts of the food produced for human consumption are lost or wasted in Portugal, corresponding to about 1 million tonnes per year. 42% of this waste corresponds to fruits and vegetables (Batista et al., 2012).

This paper consists of a further six sections. The second section describes, step by step, the methodology implemented in this study. The third section outlines the theoretical background to the study. The different outcomes are presented and discussed in section four. The fifth section provides a discussion on the appropriate mitigation strategies, taking into consideration the results of the previous section, and the sixth and final section summarises the main conclusions of this paper, highlighting the opportunities for future research.

2.2. Research Methodology

To answer the research question guiding this study, the steps presented in Figure 2.1 were executed. Firstly, a literature review (described in section 2.3) was performed to identify the causes of FLW in fresh FSCs and set their definitions. Afterwards, the Focus Group Discussion (FGD) research technique was used to assess these causes and determine which ones are relevant to the context of FVSCs. The experts were asked to establish the contextual relationships amongst the selected causes to depict their hierarchical structure, using the ISM methodology. After presenting the hierarchical structure to the experts, and their agreement regarding the consistency of the ISM-based model, MICMAC analysis was used to classify the causes according to their driving and dependence power and determine the root causes of FLW in FVSCs. The root causes of FLW were then used to discuss the mitigation strategies that should be implemented to reduce FLW in these supply chains.

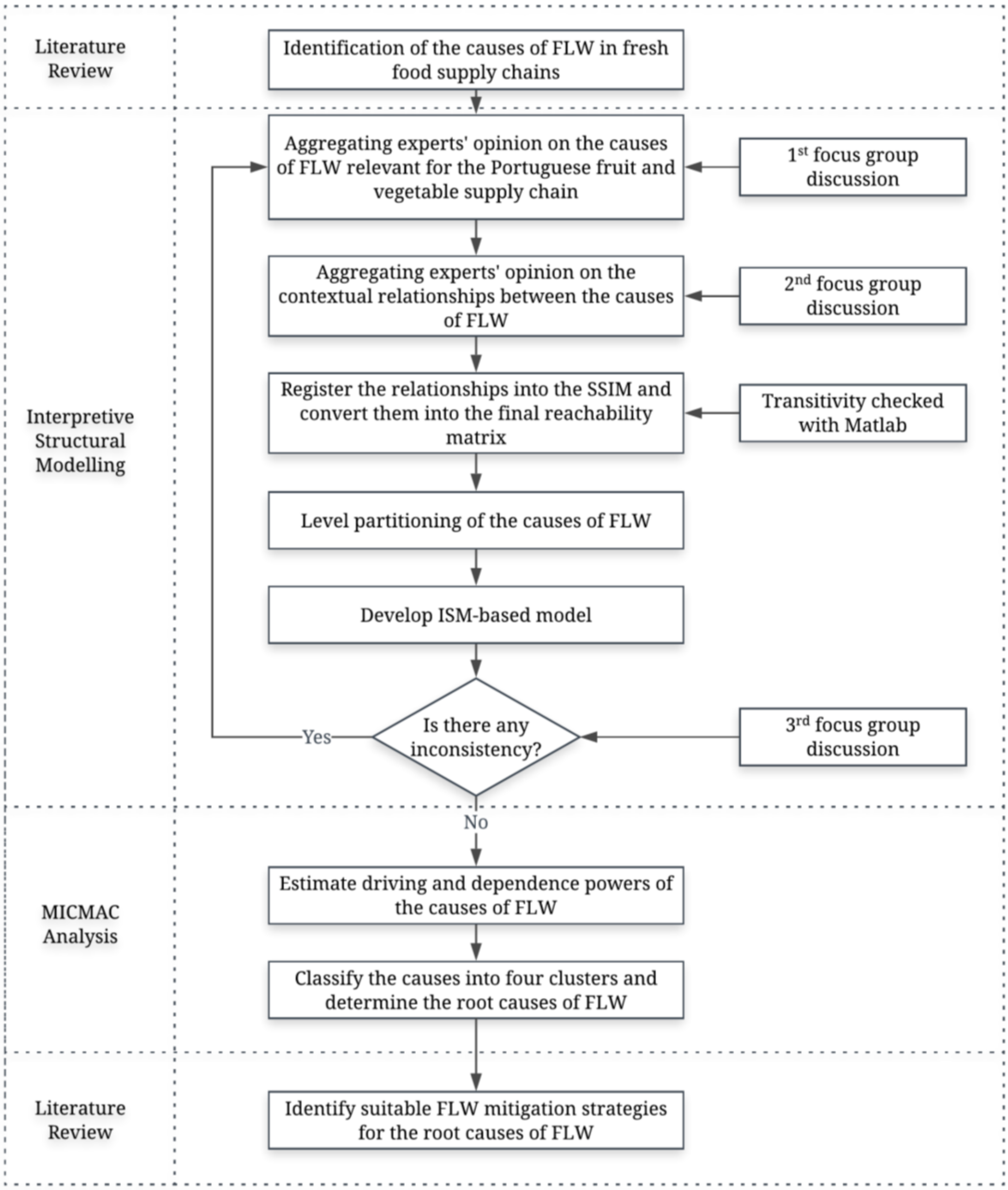

Figure 2.1 – Research methodology adopted in this study.

2.2.1 Interpretive Structural Modelling

ISM structures the relationships between the variables of a particular complex research problem (Kwak et al., 2018). It translates unclear mental models into visible and well-defined systems (Venkatesh et al., 2015) and helps to understand that system by determining the hierarchy and relationships between its variables (Kwak et al., 2018). ISM is capable of capturing dynamic complexities, while other methodologies, like Analytic Hierarchy Process (AHP) or Analytic Network Process (ANP), have trouble dealing with complex real-life problems and have less ability to capture dynamic behaviours (Shahabadkar et al., 2012).

The advantages of ISM include: (1) integrating experts' knowledge and opinion; (2) providing the opportunity to amend opinions and change the evaluations, (3) not requiring too many operations to evaluate systems with 10 to 15 variables and (4) may be appropriately applied to real conditions (Wu et al., 2015). Which is why the methodology has been widely applied in supply chain management (SCM), from vendor selection applications to supply chain risk or performance assessment (Shahabadkar et al., 2012; Sushil, 2017).

ISM is used in the present paper to identify and assess the interactions between the causes of FLW along FVSCs. The results present a graphical structural map of the causes, highlighting the connections between them and the most critical causes requiring mitigation. ISM comprises a set of well-defined steps for its successful implementation and, in this research, the works of Venkatesh et al. (2015), Mishra et al. (2017) and Kwak et al. (2018) were used to guide its implementation. To implement ISM, firstly, one must identify and list the causes comprising the system to be studied. Secondly, the contextual relationships must be identified among each pair of the identified causes and registered into a Structural Self-Interaction Matrix (SSIM). This matrix is then converted into a binary matrix (called initial reachability matrix) representing the direct relationships between the causes. To also capture the indirect relationships between them, the matrix is checked for transitivity and converted into a final reachability matrix, accounting for all the (direct and indirect) relationships between the causes. Afterwards, level partitioning is applied, arranging the elements according to their level of influence. Finally, the ISM-based model is drawn up, based on their relationships from the initial reachability matrix.

2.2.2 MICMAC Analysis

The MICMAC analysis is used to assess the driving and dependence powers of each cause (Gardas et al., 2017) and determine which are the most influential causes of FLW along the FVSC. It is usually applied after the ISM methodology. The driving power of a cause indicates the capacity that it has to influence the other causes in the system. The dependence power, on the other hand, indicates the degree to which a cause is influenced by the others. A driving-dependence power diagram was created, and the causes were classified into the four clusters of the MICMAC analysis: (1) Autonomous, (2) Dependent, (3) Linkage and (4) Independent clusters. The most important cluster for this research is the independent one, since it includes the causes that influence the majority of the others, but are almost not influenced by any of them and are, therefore, considered the root causes of FLW (Mishra et al., 2017).

2.2.3 Focus Group Discussion

The FGD research technique plays an important role in the operationalisation of the methodology proposed in Figure 2.1. FGD provides an exploratory approach and is used to gather information through the interaction of a group of experts concerning a specific subject area set by the moderator (Nassar-McMillan and Borders, 2002). The conversations can either be used to enhance information previously known about a subject or to investigate it from a different point of view, creating new insights on the matter. To do so, the moderator must assume the leadership of the conversation and stimulate discussion among the participants. The participants should be able to provide high quality information regarding the subject under study and, therefore, should be selected based on very specific criteria (Greenbaum, 1998).

Seven experts were selected, following the guidelines presented by Greenbaum (1998), to be part of one focus group, to discuss the issue of the loss and waste of food in FVSCs. The experts were chosen based on their considerable experience in producing, distributing and selling fruits and vegetables. They were selected to include players with businesses in Portugal that import, produce, distribute, sell and export different fruits and vegetables, to enable a holistic understanding of the causes of FLW along the supply chain. Their profiles are presented in Table 2.1. The insights obtained from the focus group were collected during three different discussions with average durations of approximately 90 minutes each. One of the authors moderated the discussions, since he is knowledgeable about the topics of supply chain management and FLW, and his role was to guide the discussion from general to specific topics and to help reach extensive consensuses, in order to endorse sincerity and reduce bias.

Table 2.1 – Profile of the experts

Expert	**Type of activity**	**Designation**
1	F&V Producer	Senior Operations Manager
2	F&V Producer	Operations Manager
3	Logistics Operator	Logistics and FSC Manager
4	Retailer	Procurement Manager
5	Retailer	Chief-executive of the sales department
6	Academics	Professor
7	Academics	Professor

The contribution of the focus group to this research was divided into three rounds of discussions. The participants in the focus group received an email with the list of causes of FLW encountered in the literature for fresh FSCs (see section 2.3), and their definitions, previous to the first discussion. During the discussion that followed, the experts were encouraged to talk openly about their experiences regarding FLW and were asked to confirm and agree on the definitions of the causes and their suitability for the context of the FVSC. Furthermore, they were also invited to list any other causes of FLW not referred to in the literature. The same seven experts were later invited to a second discussion to evaluate the relationships amongst the causes of FLW selected. After implementing the ISM methodology, the hierarchical structure was sent via email to these experts to check for any inconsistencies. A third discussion with this focus group was used to discuss these inconsistencies and reach a consensus on the output of the ISM methodology.

2.3. Literature Review on the Causes of Food Loss and Waste

A literature review was performed to: search and review relevant literature regarding the causes and drivers of FLW in fresh FSCs, set definitions for each cause encountered, and gather knowledge regarding the strategies used to reduce FLW.

Keywords, such as: “causes”, “mitigation strategies”, “fresh”, “supply chain” and “food loss and waste” or other waste related terms, such as “food waste”, “food loss” and “food wastage”, were used to search for relevant literature in the Scopus and Web of Science databases and in Google Scholar. Twenty-one papers were selected and reviewed, from which twenty-six causes of FLW were identified and summarised in Table 2.2. The table shows that even though some causes are specific to one stage of FSCs, the majority of them were referred to at two or more stages, indicating a need to study the problem from a holistic perspective. The table also shows whether the causes of FLW are particular to developed or undeveloped countries.

Table 2.2 – Summary of the causes of food loss and waste for the different fresh food supply chain stages

Causes	FSC Stage					Country		References
	AP	PS	PP	D	R	DC	UC	
Overproduction and excessive stock	✓		✓		✓	✓	✓	de Lange and Nahman (2015); de Steur et al. (2016); Priefer et al. (2016); Richter and Bokelmann (2016); Calvo-Porral et al. (2017); Plazzotta et al. (2017)
Inadequate demand forecasting	✓		✓		✓	✓		Mena et al. (2014); Buzby et al. (2015); de Steur et al. (2016); Priefer et al. (2016); Richter and Bokelmann (2016); Beausang et al. (2017); Kulikovskaja and Aschemann-Witzel (2017)
Poor operational performance and inadequate handling	✓	✓	✓			✓	✓	Macheka et al. (2013); Mena et al. (2014); de Steur et al. (2016); Gadde and Amani (2016); Priefer et al. (2016); Sibomana et al. (2016); Calvo-Porral et al. (2017); Corrado et al. (2017)
Climate change and weather variability	✓					✓	✓	Nahman and de Lange (2013); Mena et al. (2014); Gadde and Amani (2016); Beausang et al. (2017)
Non-conformance to retail specifications	✓	✓	✓		✓	✓		Lebersorger and Schneider (2014); Mena et al. (2014); Buzby et al. (2015); de Steur et al. (2016); Tromp et al. (2016); Beausang et al. (2017); Kulikovskaja and Aschemann-Witzel (2017)

Causes	FSC Stage					Country		References
	AP	PS	PP	D	R	DC	UC	
Product quality (deterioration and diseases contamination)	✓	✓	✓		✓	✓	✓	Mena et al. (2014); Buzby et al. (2015); Emana et al. (2017); Tesfay and Teferi (2017); Beausang et al. (2017)
Lack of infrastructures and technical/managerial skills	✓			✓			✓	Parfitt et al. (2010); Nahman and de Lange (2013); de Lange and Nahman (2015); Sibomana et al. (2016)
Not-harvested products due to unprofitable prices	✓					✓		Priefer et al. (2016); Calvo-Porral et al. (2017); Corrado et al. (2017)
Seasonality	✓					✓	✓	Gadde and Amani (2016); Plazzotta et al. (2017)
Short product shelf life or expired/near expiry products	✓	✓	✓	✓	✓	✓		Mena et al. (2014); Gadde and Amani (2016); Richter and Bokelmann (2016); Tromp et al. (2016); Calvo-Porral et al. (2017); Kulikovskaja and Aschemann-Witzel (2017)
Inadequate transportation systems	✓	✓	✓	✓		✓	✓	Mena et al. (2014); Sibomana et al. (2016); Calvo-Porral et al. (2017); Corrado et al. (2017); Kowalska (2017)
Supply chain inefficiencies (lack of coordination and information sharing)	✓	✓	✓	✓	✓	✓		Mena et al. (2014); Buzby et al. (2015); Tromp et al. (2016); Kulikovskaja and Aschemann-Witzel (2017)
Spillage	✓	✓	✓			✓		Calvo-Porral et al. (2017); Corrado et al. (2017)
Lack of storage facilities		✓	✓	✓	✓	✓	✓	Parfitt et al. (2010); de Lange and Nahman (2015); Calvo-Porral et al. (2017); Corrado et al. (2017); Kowalska (2017)
Poor stacking, filling and cushioning in bulk bins/crates		✓		✓			✓	Macheka et al. (2013)
Inadequate or defective packaging		✓	✓	✓	✓	✓	✓	Lebersorger and Schneider (2014); Mena et al. (2014); Buzby et al. (2015); Priefer et al. (2016); Corrado et al. (2017); Kulikovskaja and Aschemann-Witzel (2017)
Storage at wrong temperatures		✓	✓		✓	✓	✓	Macheka et al. (2013); Mena et al. (2014); Buzby et al. (2015); Priefer et al. (2016); Richter and Bokelmann (2016); Calvo-Porral et al. (2017); Corrado et al. (2017)
Overstock due to take-back agreements and orders cancellation		✓				✓		Priefer et al. (2016)
Poor processing and storage operations			✓			✓		Mena et al. (2014); de Steur et al. (2016); Calvo-Porral et al. (2017)
Inadequate inventory management			✓			✓		Mena et al. (2014)
Wrong labelling			✓		✓	✓		Mena et al. (2014)
Transportation at wrong temperature				✓		✓	✓	Parfitt et al. (2010); Mena et al. (2014); Calvo-Porral et al. (2017); Corrado et al. (2017)
Distance travelled				✓		✓		Mena et al. (2014)

Causes	FSC Stage					Country		References
	AP	PS	PP	D	R	DC	UC	
Pricing strategies and promotions management					✓	✓		Mena et al. (2014); Buzby et al. (2015); Priefer et al. (2016); Kulikovskaja and Aschemann-Witzel (2017)
Inadequate handling by retailers and consumers					✓	✓		Mena et al. (2014); Buzby et al. (2015); Calvo-Porral et al. (2017)
Inefficient in-store management					✓	✓		Mena et al. (2014); Buzby et al. (2015); Calvo-Porral et al. (2017)

Note: AP – Agricultural Production; PS – Post-harvest Handling and Storage; PP – Processing and Packaging; D - Distribution; R – Retail and Wholesale; DC – Developed Country; and UC – Undeveloped Country.

Some authors have worked towards the identification of the causes of FLW at the different FSC stages and for different regions (e.g., Buzby and Hyman, 2012; Affognon et al., 2015; Magalhães et al., 2019). In general, these studies consider that FLW not only depends on the stage of FSCs, but it also depends on the level of economic development of the region under study. In developing countries, FLW is more relevant in the agricultural production, post-harvest, processing and distribution stages and is mainly due to a lack of infrastructures and technical and managerial skills in food production and transportation (Bräutigam et al., 2014; Plazzotta et al., 2017). In developed countries, FLW occurs essentially at the last stages of the supply chain (Bräutigam et al., 2014), mainly because of bad coordination and communication between the different stages, as well as the consumers' attitudes (Balaji and Arshinder, 2016; Schanes et al., 2018).

Other authors attempted to classify the causes of FLW, instead of only assessing their sources and where they occurred in FSCs. Mena et al. (2011) realised that many causes in the supplier-retailer interface were interdependent and part of a complex web, classifying them into mega-trends, natural constraints and management root causes, the latter being the ones practitioners should tackle. In a posterior work, Mena et al. (2014) focused on the analysis of FLW management related causes and divided these into two groups: supply and demand management causes and quality and process control causes. Canali et al. (2017) classified the causes of FLW into: technological drivers, drivers relating to business and economy, drivers relating to legislation and policy, and social drivers. This classification was used by Willersinn et al. (2015) to investigate the influence that each group of causes had on FLW generation for the different FSC stages. It started to become clear from these studies, that different causes of FLW could have the same source, like management issues or problems related to the quality of the product.

Even though some efforts are being made to better understand why FLW occurs, Canali et al. (2017) emphasised that FLW is not generated by one or a few main factors, but results instead from an intricate net of extremely diverse and interconnected causes, also evidenced by the work of Mena et al. (2011). Furthermore, Diaz-Ruiz et al. (2018) consider that the potential that multidimensional approaches with a holistic FSC perspective have, to shed light on the core of the FLW problem, has been underestimated. This idea is reinforced by Canali et al. (2017) and Dora et al. (2019), who concluded that only approximately one third of the works they studied, regarding the levels and causes of FLW, targeted the whole FSC.

Despite the fact that the research is still very limited, some authors have recently started to use multidimensional analysis to evaluate the different causes of FLW in FSCs, in an attempt to establish the relationships and priorities between them. ISM, total interpretive structural modelling (TISM), AHP and decision making trial and evaluation laboratory (DEMATEL) were applied by Gardas et al. (2017), Balaji and Arshinder (2017), Raut et al. (2018), Gardas et al. (2018), Gardas et al. (2019a) and Gardas et al. (2019b) to assess the interrelationships between the causes of FLW, the challenges inhibiting sustainable practices and the key performance indicators in the Indian FVSC.

In conclusion, most of the literature assessing the causes of FLW focuses on the downstream stages of FSCs and often uses data taken from the literature itself, without resorting to practical or industrial data (Priefer et al., 2016). The focus is mainly on the identification of material flows and the origin of FLW and not much attention has been paid to the relationships between the different causes of FLW in fresh FSCs. Further, no efforts have been made towards analysing which FLW mitigation strategies are more suitable, given the multidimensional analysis. Therefore, the aim of this paper is to contribute to the body of knowledge regarding FLW, by developing a methodological approach (that combines a literature review with an ISM-MICMAC analysis) to: identify relevant causes of FLW in FVSCs; model their interrelationships from a supply chain perspective; determine the root causes in the Portuguese context; and use this information to discuss mitigation strategies to implement and, consequently, prevent FLW.

2.4. Development of the Integrated ISM and MICMAC Analysis

2.4.1 Identification of the Causes to be Investigated

The first step of the ISM methodology determines the causes of FLW to be investigated and these were obtained during the first discussion with the focus group. The experts were invited to evaluate which causes, gathered from the literature and listed in Table 2.2, are relevant for FVSCs and should therefore be considered. In order to guide the discussion, the moderator asked the experts a set of previously defined questions:

(1) Which are the causes applicable to fruit and vegetable supply chains?

(2) Are the definitions suitable? If not, what should be changed?

(3) Are there any similarities between the causes? If so, which ones should be integrated?

(4) Are there any other causes that have not been considered? If so, which ones?

A cause was only selected when the majority of the experts, i.e. when four or more experts, agreed upon its applicability to the FVSC. Otherwise, the cause of FLW was put aside, and considered to only play a minor role in the issue. As a result, fourteen causes of FLW emerged from the discussion. The experts did not identify other causes than the ones already encountered in the literature and considered that the causes selected were different from each other. Therefore, the 14 causes selected were the starting point for the ISM methodology and are described below.

1. **Inadequate demand forecasting** and planning of fresh products is a relevant cause of FLW. When dealing with fresh products, the combination of the typical short shelf lives with the fluctuation in demand hampers efficient ordering and often leads to overproduction. In fact, Calvo-Porral et al. (2017) state that in retail, incorrect planning concerning demand usually results in fresh products not being sold before the end of the expiry date, leading to FLW.

2. **Overproduction and excessive stocks** along FSCs is another cause of FLW. Overproduction may be a consequence of inaccuracy in predicting demand, but for the producers of fresh products, overproduction is usually the result of agreements with retailers (Priefer et al., 2016). Along FSCs, overproduction and excessive stocks are also a consequence of FSCs not adopting pull strategies (de Steur et al., 2016).

3. **Poor handling/poor operational performance** along FSCs leads to mechanical and microbial spoilage of fresh products, leading to FLW (Macheka et al., 2013; de Steur et al., 2016). The rough handling, by different members of FSCs, combined with the stage of maturity, which affects the products' ability to withstand compression and puncture wounds, often results in mechanical damage and affects the products' shelf life, accelerating physiological and microbial damage (Sibomana et al., 2016).

4. **Storage at wrong temperature** leads to mechanical and microbial damage from excessive or insufficient temperature or humidity, leading to FLW (Buzby et al., 2015). Whether because of the lack of cold storage or by the interruption of the cold chain, fresh products are prone to develop physiological defects such as freezing, chilling, sunburn, sunscald and internal breakdown (Macheka et al., 2013; Priefer et al., 2016). Mena et al. (2014) mention that this only happens because there is a poor adherence to temperature controls during storage, transportation, and retail.

5. **Inadequate or defective packaging** is another cause of FLW in FSCs. Lebersorger and Schneider (2014) and Priefer et al. (2016) mention that sometimes the packaging can be damaged without damaging the product itself (e.g., an open tray of apples), but that it often does damage the product (e.g., a smashed yoghurt pot), leading to FLW. The fact that some fresh products are packaged together might also generate FLW (e.g., a rotten apple in a bag of apples might be left unsold) (Buzby et al., 2015).

6. **Non-conformance to retail specifications** is also a relevant cause of FLW. Since consumers are becoming more demanding, retailers and producers have developed tight requirements concerning the appearance and the quality of products, which often leads to FLW (Mena et al., 2014). The incorrect weight, unsuitable sizes, shapes or textures of fresh products and visible mechanical or microbial defects are some of the specifications set by retailers that promote their exclusion, even though they may still be suitable for human-consumption (de Steur et al., 2016).

7. **Sensorial or microbial deterioration** is related to the natural deterioration of the physiological, biochemical and microbiological properties of fresh products. When this deterioration is accelerated by factors such as temperature and humidity, then fresh products may reach their expiry date sooner than expected or develop visible defects that lead to their rejection (Buzby et al., 2015; Emana et al., 2017; Tesfay and Teferi, 2017). Diseases and insect pests can also significantly affect the microbiological deterioration rate of fresh products (Mena et al., 2014; Emana et al., 2017).

8. **Short product shelf life or expired products** are another cause of FLW. Fresh products are discarded because of reaching the end of the best-before, or sell-by dates, or by decisions made along FSCs that compromise the products' shelf life. In retail, the uncertainty of the demand and replenishment policies influence the level of inventory, which leads to stocking products with different expiry dates, leading to FLW (Tromp et al., 2016). Fresh products can also be left unsold, since the consumers prefer products with longer expiry dates, perceiving that a product close to its expiry date is not so fresh anymore (Mena et al., 2014).

9. **Climate change and weather variability** can lead to crop losses in the field. Indeed, extreme weather events may cause visible cosmetic damage to crops, leading to their rejection because of retail specifications (Beausang et al., 2017). Retail specifications may also change in response to weather variations, influencing the level of product rejections. Mena et al. (2014) state, for example, that during the warmer months greener bananas are preferred to extend their shelf life in stores. Farmers also produce more than what is set out in their contracts with the retailers, in order to cope with possible unforeseen weather events, leading to unnecessary overproduction that can end up as waste (Beausang et al., 2017).

10. **Lack of storage facilities** is directly related to the interruption of the cold chain, leading to fresh products' quality deterioration. For example, Parfitt et al. (2010) estimate that 30% of the fresh fruit and vegetable production in India is wasted because of the lack of appropriate or sufficient storage facilities.

11. **Pricing strategies and promotion management** is also a cause of FLW. Mena et al. (2014) concluded that the recent economic recession and increase in the prices of food are shifting the consumers shopping routines. Consumers are, therefore, seeking supermarkets with

lower food prices or buying larger amounts when a product is on promotion. However, some promotions can cause in-store FLW, due to poor accuracy in predicting demand (Buzby et al., 2015). The promotions are planned in the long run, which may inhibit the retailer's ability to maintain a quick turnaround and respond to sudden gluts of supply or of surpluses at times of high availability. This promotes FLW. Despite their careful planning, promotions seem to contribute to more unpredictable demand patterns, affecting not only the products on promotion, but also the sales of substitute products (Mena et al., 2014).

12. **Lack of coordination and information sharing** amongst the stakeholders of FSCs is also a relevant cause of FLW. Mena et al. (2014) argue that the closer the relationships between retailers and suppliers, the lower the levels of FLW in FSCs are. Furthermore, transparency and sharing of information allow retailers to launch supply driven promotions, consequently reducing FLW and increasing turnover (Mena et al., 2014). Priefer et al. (2016) also state, for example, that if retailers have an inadequate prediction of demand, it will result in orders that later have to be cancelled and this will result in FLW and will erase the gains in efficiency made in the food industry.

13. **Inadequate transportation systems** also lead to FLW in FSCs, since they result in mechanical, physiological and microbial damage to fresh products, which promote their rejection by failing to comply with retail specifications or because of the products lack of quality (Sibomana et al. 2016). Furthermore, the authors state that the lack of transport infrastructures also constrains the accessibility to markets, leading to delays in deliveries, making it difficult for fresh products to reach the shelves of the supermarkets with sufficient shelf lives.

14. **Inefficient in-store management** is the last cause of FLW in FSCs considered. Consumers expect the shelves of the supermarkets to be packed with a wide range of fresh products, but the large quantities on display and the wide range of available products result in excess stocks and oversupplying, leading to the fresh products remaining unsold and ending up as waste (Calvo-Porral et al., 2017). Other in-store decisions such as: product placement, the visual display, the layout criteria and the back-store management, also influence FLW levels (Mena et al., 2014; Calvo-Porral et al., 2017). For example, the exposure to light decreases the longevity of certain fresh products, leading to in-store FLW (Buzby et al., 2015).

2.4.2 Structural Self-Interaction, Initial and Final Reachability Matrices

The 14 causes of FLW generate 91 (14 times 13, divided by 2) different links between them. These links represent their interrelationships. A second discussion with the focus group was held to assess those contextual relationships. To capture and analyse the relationships between the causes, the experts were asked to use four letters to represent the direction of the relationship between each pair of causes. V meaning that cause i influences cause j; A meaning that cause j influences cause i; X meaning that causes i and j influence each other; and O meaning that causes i and j are unrelated. However, as the different experts could evaluate each relationship differently, the contextual relationships between the causes was determined by the rule suggested by Shen et al. (2016), that "the minority gives way to the majority". Therefore, the moderator considered that a consensus was reached when the majority agreed on a contextual relationship. The direct relationships were put in the Structural Self-Interaction Matrix (SSIM) shown in Table 2.3.

Table 2.3 – Structural Self-Interaction Matrix

C[i/j]	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	-	X	O	O	O	O	O	V	O	O	X	A	O	O
2		-	O	O	O	O	V	V	O	A	X	A	O	O
3			-	O	A	V	V	V	O	O	O	O	O	V
4				-	O	V	V	V	O	A	V	A	A	A
5					-	V	V	V	O	O	O	O	A	O
6						-	X	V	A	A	O	A	A	O
7							-	V	A	A	V	A	A	A
8								-	O	A	V	A	A	A
9									-	O	V	O	O	O
10										-	O	O	O	V
11											-	A	O	O
12												-	O	O
13													-	O
14														-

Note: C[i/j] represents the cause in line i or in column j.

SSIM was transformed into a binary matrix (hereafter called the initial reachability matrix, IRM), shown in Table 2.4, by substituting V, A, X and O with 1s and 0s, according to the following rules:

- If the (i, j) entry in the SSIM is V, then the (i, j) entry in the IRM becomes 1 and the (j, i) entry becomes 0;
- If the (i, j) entry in the SSIM is A, then the (i, j) entry in the IRM becomes 0 and the (j, i) entry becomes 1;
- If the (i, j) entry in the SSIM is X, then the (i, j) and (j, i) entries in the IRM become 1;
- If the (i, j) entry in the SSIM is O, then the (i, j) and (j, i) entries in the IRM become 0.

The IRM was subsequently checked for transitivity with a Matlab routine to avoid human error. If cause i is directly related to cause j and cause j is directly related to cause k, then causes i and k are indirectly related, by means of the cause j, and if the entry (i, k) of the IRM was 0, then it must be replaced by a 1*. This transforms the IRM into the final reachability matrix (see Table 2.5) that accounts for all (direct and indirect) relationships between the causes. Driving and dependence powers were also calculated in this step, to assist the MICMAC analysis.

Table 2.4 – Initial Reachability Matrix

C[i/j]	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	1	0	0	0	0	0	1	0	0	1	0	0	0
2	1	1	0	0	0	0	1	1	0	0	1	0	0	0
3	0	0	1	0	0	1	1	1	0	0	0	0	0	1
4	0	0	0	1	0	1	1	1	0	0	1	0	0	0
5	0	0	1	0	1	1	1	1	0	0	0	0	0	0
6	0	0	0	0	0	1	1	1	0	0	0	0	0	0
7	0	0	0	0	0	1	1	1	0	0	1	0	0	0
8	0	0	0	0	0	0	0	1	0	0	1	0	0	0
9	0	0	0	0	0	1	1	0	1	0	1	0	0	0
10	0	1	0	1	0	1	1	1	0	1	0	0	0	1
11	1	1	0	0	0	0	0	0	0	0	1	0	0	0
12	1	1	0	1	0	1	1	1	0	0	1	1	0	0
13	0	0	0	1	1	1	1	1	0	0	0	0	1	0
14	0	0	0	1	0	0	1	1	0	0	0	0	0	1

Note: C[i/j] represents the cause in line i or in column j.

Table 2.5 – Final Reachability Matrix

C[i/j]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	DVP
1	1	1	0	0	0	1*	1*	1	0	0	1	0	0	0	6
2	1	1	0	0	0	1*	1	1	0	0	1	0	0	0	6
3	1*	1*	1	1*	0	1	1	1	0	0	1*	0	0	1	9
4	1*	1*	0	1	0	1	1	1	0	0	1	0	0	0	7
5	1*	1*	1	1*	1	1	1	1	0	0	1*	0	0	1*	10
6	1*	1*	0	0	0	1	1	1	0	0	1*	0	0	0	6
7	1*	1*	0	0	0	1	1	1	0	0	1	0	0	0	6
8	1*	1*	0	0	0	0	0	1	0	0	1	0	0	0	4
9	1*	1*	0	0	0	1	1	1*	1	0	1	0	0	0	7
10	1*	1	0	1	0	1	1	1	0	1	1*	0	0	1	9
11	1	1	0	0	0	1*	1*	1*	0	0	1	0	0	0	6
12	1	1	0	1	0	1	1	1	0	0	1	1	0	0	8
13	1*	1*	1*	1	1	1	1	1	0	0	1*	0	1	1*	11
14	1*	1*	0	1	0	1*	1	1	0	0	1*	0	0	1	8
DPP	14	14	3	7	2	13	13	14	1	1	14	1	1	5	

Note: C[i/j] represents the cause in line i or in column j; DPP – Dependence Power; DVP – Driving Power.

2.4.3 Level Partitioning

After developing the final reachability matrix, level partitioning was conducted. For each variable, the reachability set, the antecedent set and the intersection set were found, to assess the levels of the variables. The reachability set is the sum of the entries equal to 1s for each line (indicating that variable i influences variable j), the antecedent set is the sum of the entries equal to 1s for each column (indicating that variable i is influenced by variable j) and the intersection set comprises the duplicate variables from the reachability and antecedent sets. When the intersection set is equal to the reachability set, then the variable is attributed to the level of that iteration. The variables assigned to one level are then removed from the remaining reachability and intersection sets for the next iteration and the same process is applied until all the variables are partitioned into levels.

Table 2.6 illustrates the level partitioning results of the 14 causes under study and four causes are considered as the top-level of the ISM-based model: cause 1 – inadequate demand forecasting; cause 2 – overproduction and excessive stock; cause 8 – short shelf life or expired products; and cause 11 – pricing strategies and promotion management. After removing these from the remaining reachability and intersection sets, the next level causes are causes 6 and 7, non-conformance to retail specifications and product quality, respectively. After seven iterations, the bottom level of the ISM-based model was found.

Table 2.6 – Level partitioning results

Causes	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,2,6,7,8,11	1,2,3,4,5,6,7,8,9,10,11,12,13,14	1,2,6,7,8,11	I
2	1,2,6,7,8,11	1,2,3,4,5,6,7,8,9,10,11,12,13,14	1,2,6,7,8,11	I
3	3	3,5,13	3	V
4	4	3,4,5,10,12,13,14	4	III
5	5	5,13	5	VI
6	6,7	1,2,3,4,5,6,7,9,10,11,12,13,14	6,7	II
7	6,7	1,2,3,4,5,6,7,9,10,11,12,13,14	6,7	II
8	1,2,8,11	1,2,3,4,5,6,7,8,9,10,11,12,13,14	1,2,8,11	I
9	9	9	9	III
10	10	10	10	V
11	1,2,6,7,8,11	1,2,3,4,5,6,7,8,9,10,11,12,13,14	1,2,6,7,8,11	I
12	12	12	12	IV
13	13	13	13	VII
14	14	3,5,10,13,14	14	IV

2.4.4 ISM-based Model

A direct graph, or digraph, is built by arranging the variables vertically and horizontally according to the level partitioning and, if variable i influences variable j in the initial reachability matrix, then an arrow is used, pointing from i to j, to show the direct influence between these two variables. The ISM-based model, shown in Figure 2.2, demonstrates the hierarchical structure of the causes of FLW and highlights their interrelationships. The digraph was generated by arranging the 14 causes according to the level partitioning (Table 2.6) and by connecting the causes according to the initial reachability matrix (Table 2.4). The digraph was sent to the focus group by email and a third discussion was held to evaluate inconsistencies in the model. The experts agreed that no inconsistencies were found, so the research team continued to the MICMAC analysis.

The levels of the different causes of FLW in the ISM-based model provide an understanding of their impact in the reduction of FLW in FVSCs. Figure 2.2 shows that inadequate demand forecasting, overproduction and excessive stock, pricing strategies and promotion management and the short shelf life or expired products are the causes of FLW from the first level of the ISM-based model. The second level comprises the non-conformance to retail specifications and the sensorial or microbial deterioration. Given the ISM methodology, if practitioners implement actions to eliminate the causes from level II, these actions will also help to eliminate the causes from level I. At the bottom of the ISM hierarchy is the inadequate transportation systems, corresponding to level VII of the ISM methodology, which is the cause that has most influence over the other causes of FLW considered. This is the most influential cause under study and consequently actions taken at lower levels will have little or no repercussion at higher levels.

A MICMAC analysis was used to further assess what causes of FLW are the root causes of the wastage and need to be tackled in FVSCs.

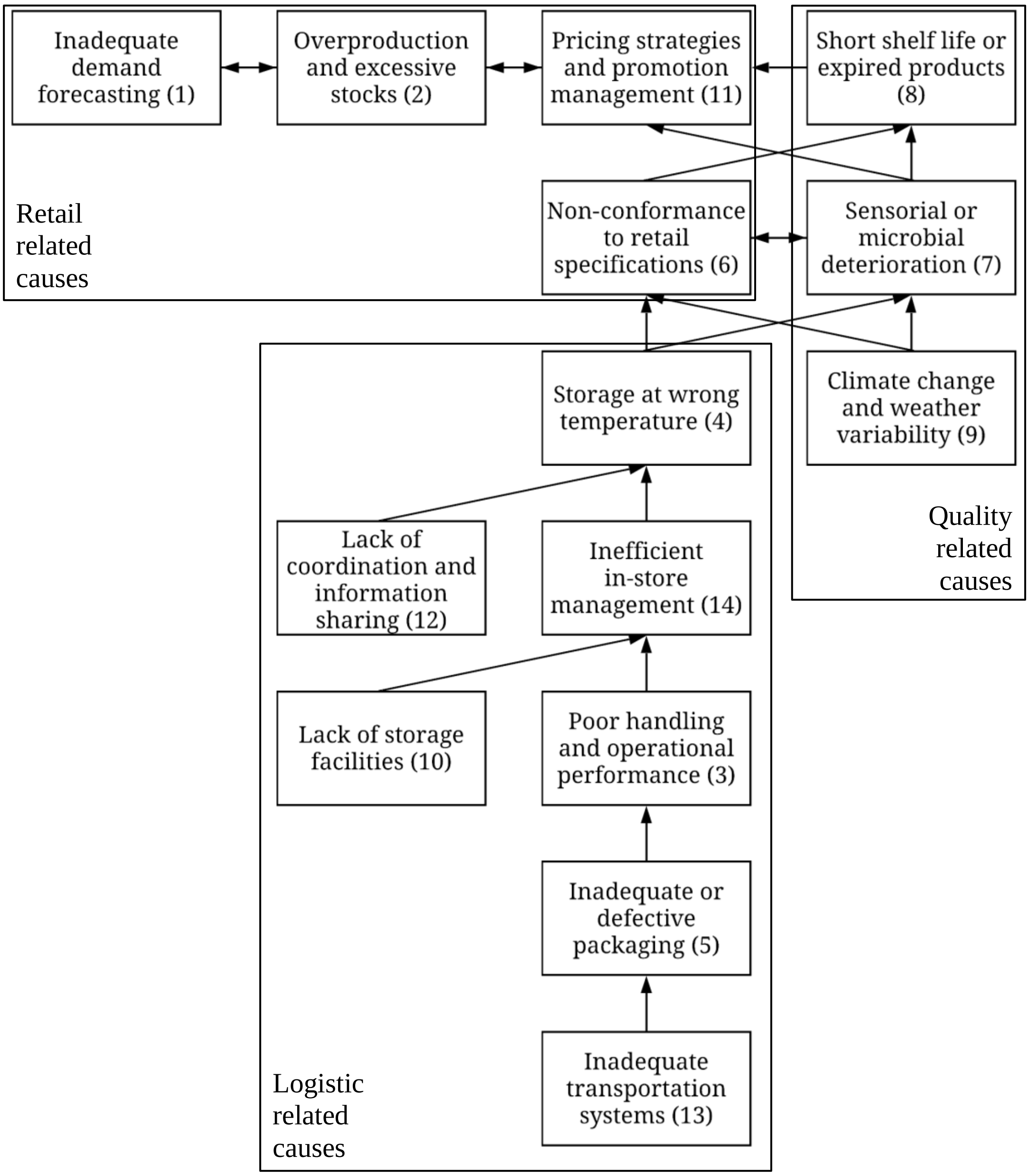

Figure 2.2 – ISM-based model of the causes of food loss and waste in fresh food supply chains.

2.4.5 MICMAC Analysis

The driving and the dependence powers of each cause under analysis are shown in Table 2.5. In the final reachability matrix, the sum of each row determines the causes' driving power and the sum of each column determines the causes' dependence power. Subsequently, a driving-dependence power diagram is constructed, and the causes are classified into four clusters, as shown in Figure 2.3.

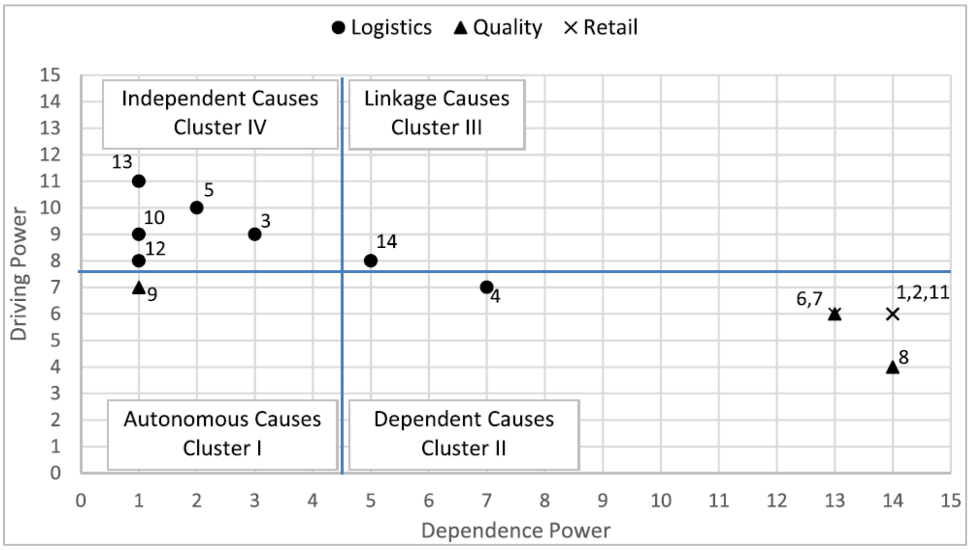

Figure 2.3 – MICMAC analysis of the causes of food loss and waste.

Figure 2.3 shows that climate change and weather variability (cause 9) is the only autonomous cause present in the first cluster. This cause has weak driving and dependence powers and has little influence over the other causes of FLW investigated. Which, from a supply chain perspective, is easy to understand, since the climate change and weather variability only has an effect at the producer level, not compromising the rejection of food at the other FSC stages.

The second cluster, comprising the dependent causes, has weak driving and strong dependence power. Inadequate demand forecasting (cause 1), overproduction and excessive stocks (cause 2), storage at wrong temperatures (cause 4), non-conformance to retail specifications (cause 6), sensorial or microbial deterioration (cause 7), short shelf life or expired products (cause 8) and pricing strategies and promotion management (cause 11) are dependent causes. Strong dependence indicates that these causes require all the other ones to mitigate FLW, i.e. these causes are strongly influenced by the other causes of FLW considered, but do not have a big capacity to influence the other causes.

The third cluster, regarding the linkage causes, has strong driving and dependence powers and includes only the inefficient in-store management (cause 14). This FLW cause is quite unstable, given the fact that any action concerning it will have an effect on the others and on itself, which means that it is highly influential on the others, but also strongly influenced by them, making it difficult to assess whether changing it would be beneficial or not for the whole system.

The fourth cluster includes the independent causes having strong driving, but weak dependence power. Since these causes influence the majority of the others, but are almost not influenced by any of them, then they are considered the key or root causes of FLW in FVSCs. Poor handling and operational performance (cause 3), inadequate or defective packaging (cause 5), lack of storage facilities (cause 10), lack of coordination and information sharing (cause 12) and inadequate transportation systems (cause 13) are then the five root causes of FLW, according to the MICMAC analysis shown in Figure 2.3.

2.4.6 Discussion

After building and assessing the hierarchy of the ISM-based model, we realised that the causes were organised into three groups: logistic, quality and retail related causes (Figure 2.2). The FLW logistic related causes incorporate inadequate transportation systems, inadequate or defective packaging, lack of storage facilities, poor handling and operational performance, lack of coordination and information sharing, inefficient in-store management and storage at the wrong temperatures. FLW quality related causes comprise climate change and weather variability, the sensorial or microbial deterioration and the short shelf life or expired products. The FLW retail related causes include the non-conformance to retail specifications, the pricing strategies and promotion management, the overproduction and excessive stocks and the inadequate demand forecasting. The results show that the logistic causes are the most influential ones and that if some actions were taken to mitigate these causes, then they would have a significant influence concerning the quality and retail related causes as well. Therefore, practitioners should focus their efforts on combating the logistic related causes first and only then should solutions be sought concerning the quality and the retail related causes of the FVSC. The work of Liljestrand (2017) also discusses the use of different logistic solutions to prevent FLW, supporting our conclusions regarding the influence that logistic related causes have on driving FLW throughout FSCs.

These findings are corroborated by earlier studies from the literature. As already stated in the literature review section, Mena et al. (2014) categorised the causes of FLW into supply and demand management causes, including here causes related to planning, forecasting and information flow, promotion management and availability and inventory management. This first category is very much in line with the retail related causes from Figure 2.2. The second category considered by Mena et al. (2014) is the quality and process control causes, including the ones related to the product specifications, control of the process, management of the shelf life and packaging and labelling. Although it is a bit different, this category still includes some causes that in Figure 2.2 are related to quality and to logistics. Gardas et al. (2018) concluded that the lack of proper packaging and storage facilities and the unsuitable transport infrastructures were the most significant causes of FLW in the FVSC in India. This is also very much in line with the results previously presented here. Balaji and Arshinder (2016) found that a poor logistics infrastructure was the most influential FLW cause. Gardas et al. (2017) concluded that the lack of packaging facilities was also of upmost importance to the same supply chain and that, in the opinion of the experts from the industry, the lack of backward and forward integration from producers to consumers played an important role in driving the other causes of FLW. These causes also proved to have major influence on the other causes of FLW considered.

However, some results contradict, to some extent, the present study. For example, Balaji and Arshinder (2016) consider that the ineffective management of demand has a high driving power and is only influenced by the poor logistics infrastructure, but, in the present research, this cause of FLW is highly dependent on pretty much all the other causes. Raut et al. (2018) also considered that the climate and weather conditions are the second most significant causes of FLW, which is not supported by this study.

Despite belonging at the least influential levels, the ISM-based model reveals a group of FSC causes related only to retail, that have consequences at several FSC stages other than retail (see Table 2.2), evidencing the pressure that retailers exert in FVSCs, particularly in Portugal. With the exception of the non-conformances to retail specifications, both the inadequate demand forecast and the excessive stock are very dependent on the aggressiveness of the pricing strategies and promotions management. Indeed, this scenario is very plausible in a country where the retailers influence consumers to take advantage of bargains.

When it comes to comparing the results from the MICMAC analysis, with the ones encountered in the literature, Gardas et al. (2017) reported that improper packaging and the lack of integration from farmers to consumers are also root causes of FLW in the Indian fruit and vegetable sector. However, the rest of the results diverge from the ones presented in Figure 2.3. The same author further concluded that, from the stakeholders' perspective, the inefficient demand forecasting was a root FLW cause, when in our case this is a dependent cause with much more potential to be influenced by the others rather than influencing them. In the same analysis, Gardas et al. (2017) classified the lack of storage facilities and the inefficient transportation and infrastructures as dependent causes of FLW, which is contrary to our analysis that shows that these are two of the most influential causes of FLW in FVSCs. Balaji and Arshinder (2016) further considered that the lack of storage facilities, the lack of coordination along FSCs and the inaccurate demand forecasting were linkage causes of FLW, which is not what we concluded in this study, since the former two are actually root causes of FLW and the latter, as said before, belongs to the dependent cluster. These differences may be explained by the fact that different countries are targeted by these studies, when compared to our own.

From the MICMAC analysis, it is also evident that the root causes of FLW, belonging to the independent cluster (see Figure 2.3), are all logistic related causes (see Figure 2.2). Note also that these are transversal to almost all stages of FSCs (see Table 2.2), reinforcing the need to study and implement mitigation strategies at the supply chain level. Although the integrated ISM and MICMAC methodology, implemented in this study, evaluates the interrelationships between the causes of FLW from the Portuguese perspective, the findings were validated by the experts and are considered to be representative of the dynamics encountered in developed countries, since the 14 causes under analysis have all been experienced in developed countries (see Table 2.2). We believe that the approach proposed here could be replicated in other contexts to guide the selection of the best practices but a holistic perspective of the issue should always be maintained, otherwise the results are bound to be irrelevant.

2.5. Implications for FLW Mitigation Strategies

The results presented previously highlight the fact that the causes of FLW in FVSCs can be grouped in logistic, quality and retail related causes, and that actions taken to mitigate the logistic causes will have an influence on the quality and retail-related causes too. This outcome is supported by the MICMAC analysis, since the five root causes of the problem are the poor handling and operational performance, the inadequate or defective packaging, the lack of storage facilities, the lack of coordination and information sharing and the inadequate transportation systems; all of which are part of the logistic related causes (see Figure 2.2). Therefore, practitioners of FVSC need to seek solutions to mitigate the logistic causes before anything else, since these are the most pressing causes of FLW to be eliminated from these supply chains and since they help to mitigate the other causes studied too.

To mitigate FLW along the different FSC stages, the solutions implemented need to tackle the aforementioned root causes directly. A literature review was performed to ascertain the strategies that practitioners should consider to prevent FLW within their businesses. The outcome is described below and the strategies are discussed in the light of each root cause.

1. **Poor handling and operational performance -** Solutions that help to minimise human influence on the deterioration of the quality of fresh products are crucial to mitigate FLW in the different FSC stages. Stakeholders should promote such awareness among employees and offer training on handling practices to improve employees' behaviour and ensure adherence to standard procedures. These procedures should be available for consultation in the form of a manual (Macheka et al., 2013).

2. **Inadequate or defective packaging** – Packaging solutions that help to preserve the fresh products longer also promote FLW reduction. To reduce FLW, stakeholders need to: (1) develop and use intelligent packaging to monitor the safety and quality of the product (Verghese et al.,

2015); (2) adjust the packaging size to match consumers' needs (Richter and Bokelmann, 2016); (3) implement correct date marking to avoid consumers' confusion (Wikström et al., 2014; Verghese et al., 2015); and (4) develop innovative packaging and preservation techniques to enhance the products' shelf life (Mercier et al., 2017). Many packaging technologies, such as modified atmosphere packaging (MAP), active packaging and intelligent packaging, and the integration on packaging of time-temperature indicators (TTIs), radio-frequency identification data (RFIDs) or freshness indicators and sensors, are already in use or under development. They will help extend the shelf life of fresh products and monitor the quality levels throughout FSCs and, consequently, reduce FLW (Verghese et al., 2015). Edible coatings with natural additives, new coatings using nanotechnological solutions and nonconventional atmospheres have also shown great potential in extending the shelf life of fresh products (Ghidelli and Pérez-Gago, 2018). It is estimated in the 2018 European Commission report, regarding food labels and food waste prevention, that the retail waste prevented by extending a product's shelf life by just one day represents, on average, 0.3% of total sales, revealing the economic impact these solutions may have on a business and the significance that packaging solutions have on the reduction of FLW.

3. **Lack of storage facilities -** Munesue et al. (2015) point out that one of the corrective actions concerning FLW reduction is to invest in infrastructures and more suitable cold chain facilities. Further, Emana et al. (2017) state that to reduce FLW there also needs to be an improvement in the cooling methods employed by the storage facilities. Another good practice is to perform regular maintenance in those facilities (Tesfay and Teferi, 2017). In general, maintaining the appropriate cold storage of fresh products can minimise FLW, because it may: provide a better control of moisture, mould proliferation and wilting; slow down the products' respiration rate; extend the products' shelf life and inhibit the development of pathogens causing accelerated quality decay (Emana et al., 2017).

4. **Lack of coordination and information sharing -** Kaipia et al. (2013) concluded that good communication among FSCs stages reduces uncertainty, enables FSCs to respond effectively to disruptions and is critical for optimal decisions. To further improve FSCs performance, Balaji and Arshinder (2016) state that integrated IT systems help to standardise the transactions of fresh products between buyers and suppliers and promote effective decision-making. Automated demand forecasting systems, based on better information flows, also help to eliminate the gap between supply and demand. However, these systems are highly dependent on the stakeholders' will to share information. Improved coordination between the stakeholders helps to build trust and commitment among the players, thereby making them more competitive and productive. The authors also say that information about the remaining shelf life, based on continuous monitoring, helps to respond faster and to implement corrective actions before the

fresh products deteriorate below a certain level of quality. Continuous monitoring is achieved through traceability systems, which enable the tracing or tracking of a fresh product throughout its journey, improving visibility along FSCs and promoting safe and quality food.

5. **Inadequate transportation systems -** The transportation systems need to be improved to reduce FLW along FSCs. Indeed, Gardas et al. (2017) concluded that some marketing channels, particularly in undeveloped countries, are too long and vary significantly based on location and on commodity. More links between the buyers and suppliers are needed to improve the efficient flow of fresh products and decrease delays in deliveries. Not only should the infrastructures be improved, but the means of transportation also need to be efficient to reduce the quality deterioration of the fresh products due to interruption of the cold chain or to the mechanical damage endured by the fresh product, due, for example, to vibrations.

Ultimately, the main objective of the different mitigation strategies previously discussed is to increase the fresh products' shelf life and decrease the probability of a product reaching a quality threshold before its consumption. When a mitigation strategy is defined and an action is taken, the expected outcome is for the loss of the product's quality to be slower and for its quality to increase for the same storage time, thus the product would reach the quality threshold at a later time than when no action was taken. However, Amani and Gadde (2015) remind researchers that the relation between shelf life extension and FLW reduction might not be so simple, since the complex consumption patterns (e.g. shopping in bulk increases storage times at households) and the complexity of the links in FSCs may lead fresh products to reach the expiry date before expected. Liljestrand (2017) also referred to the importance of logistic solutions to combat FLW in FSCs and supported the usefulness of extending the product's shelf life to reduce FLW. Seven of the solutions presented are intended to avoid reaching the expiration dates and the other two attempt to reduce damage to packaging. The author stresses the need to involve different actors in FSCs and to rely on coordination mechanisms, such as joint decision-making and information sharing, to successfully implement the solutions.

Stakeholders must also bear in mind that some solutions to FLW mitigation are very dependent on the stage of FSCs and of the regions in which they are being applied. Indeed, there is no universal solution to FLW mitigation. It is still unclear which strategies to reduce FLW are most effective, because evaluations of FLW mitigation strategies are scarce (Thyberg and Tonjes, 2016).

2.6. Conclusions

This paper contributes to the FLW literature by developing a methodological approach, combining a literature review with an ISM-MICMAC analysis, to identify the causes of FLW and model their relationships, enabling the selection, design and implementation of effective mitigation strategies to successfully combat the global challenge of FLW along FSCs. Firstly, 14 causes of FLW in fruit and vegetable (one of the most wasted categories of fresh products) supply chains, for a developed country are identified. Then, the causes are structured into a hierarchy, highlighting their relationships and identifying which have a greater influence on the others. After that, the root causes of FLW in FVSCs are identified. Finally, results from the previous steps are used to discuss the mitigation strategies that should be implemented to reduce FLW in FVSCs.

Other authors have tried to establish relationships and identify root causes of FLW in fresh FSCs. While this paper supports some of the findings from previous authors, it also points out some considerable differences, mainly concerning the root causes of FLW. These differences may be explained by the fact that those previous studies were conducted considering different economic contexts and products. This indicates that FLW in fresh FSCs also depends on these two parameters. The methodological approach proposed in this paper could also be used to tackle the root causes of FLW for different countries and products.

The findings of this paper also provide valuable insights for practitioners. They reveal the nature of the interdependent relationships, which contributes towards the design of policies to effectively facilitate the mitigation and prevention of FLW, by providing important insights concerning the priority of allocating resources and efforts to address these causes. The discussion on the mitigation strategies also provides suggestions to practitioners about what can be done to eliminate the most influential causes of FLW within their businesses.

One limitation of this study is the fact that the ISM analysis is dependent on the opinions of experts. Although the results are most likely representative of other developed countries, where retail has a predominant role concerning the FVSC, the proposed approach should be replicated in other countries with different supply chain dynamics, to assess their impact on the relationships between the causes of FLW. Future studies could also replicate the approach proposed here for other commodities to assess how different the relationships between the causes are, and what consequences they will have, concerning the most suitable mitigation strategies. Finally, future studies regarding which mitigation strategies constitute suitable solutions to reduce FLW in FSCs, and how these should be selected and implemented are also needed, since traditional discussions are only descriptive and theoretical and do not account for, or measure, the real impact each strategy has on the level of FLW or ascertain its effectiveness in preventing FLW.

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Chapter 3

Food Loss and Waste in the Brazilian Beef Supply Chain: an Empirical Analysis[2]

Abstract

Purpose - The livestock sector contributes significantly to the Brazilian economy, but also creates many environmental and social issues. To mitigate these issues and help counteract the effects of the growing production demand, it is essential to address the prevention of food loss and waste (FLW). Therefore, the aim of the present study is to identify the causes of FLW, model their interrelationships and determine their root causes for the Brazilian beef supply chain (SC).

Design/methodology/approach – Sixteen causes are analysed using an integrated Interpretive Structural Modelling (ISM) and Matrix Impact of Cross Multiplication Applied to Classification (MICMAC) methodology. ISM identified interrelationships among the causes and MICMAC determined the root causes of FLW.

Findings – The ISM highlights the "Lack of transportation infrastructures", "Inadequate handling", "Poor operational performance", "Variety of products available in supermarkets" and "Unhealthy animals and outbreaks of disease" as the most influential causes of FLW and the MICMAC classifies them as the root causes of FLW in the Brazilian beef SC.

Practical implications - The results provide fundamental insights for researchers, practitioners and policymakers, by exploring which causes are more influential and determining which are the root causes, thereby assisting the SC members in the definition of suitable strategies to mitigate FLW.

Originality/value - This is the first empirical analysis of the interdependencies between the causes of FLW in the beef SC.

Keywords: Food wastage; Root causes; Meat; ISM methodology; MICMAC analysis; Brazil.

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3.1. Introduction

One third of the food produced globally for human consumption is lost within the supply chain (SC) or wasted at the consumer end and is worth around US$ 680 billion per year in developed countries and approximately US$ 310 billion per year in developing ones (Mishra and Singh, 2018). In Latin America alone, over 127 million tonnes of food (from which 20% corresponds to meat) are lost or wasted each year, which would be enough to satisfy the dietary requirements of 300 million people (FAO, 2016). The food loss and waste (FLW) problem started drawing attention on the various media outlets recently, but there are few data, figures and relevant information available on FLW, as well as few scientific publications for developing countries (Chen et al., 2017), particularly regarding the BRIC economies (Xue et al., 2017).

FLW has been given more attention worldwide. However, there is still not a unique definition and, consequently, a unique standard method to quantify it (Lemaire and Limbourg, 2019). There is; however, an agreement in the literature concerning the urgency to study and tackle the FLW problem, especially knowing the negative impact it can have on human health and on the quality of the environment (soil, water, air and landscapes) (Neff et al., 2017; Ferreira et al., 2018). For the purpose of this study, the term FLW will be used to address all food intended for human consumption discarded along the food SC. Many Latin American countries, namely Brazil, have acknowledged the need to combat FLW and have adhered to the UN's 2030 Agenda (United Nations, 2015). Yet, Brazil struggles to simultaneously reduce FLW, promote SC sustainability and ensure food security, due to the repeated economic and social crises, and to its heterogeneous society with significant inequalities in incomes (Henz and Porpino, 2017). In 2013, Brazil lost 26.3 million tons of food from the 268.1 available (nearly 10% of the total food available) (CAISAN, 2018). However, another study states that FLW in Brazil may be as high as 42% (Dal' Magro and Talamini, 2019), denoting the need for a standard method to quantify it. Despite being a major player in world food production, Brazil is supposedly amongst the 10 nations that waste the most food (Moura et al., 2013). This concern is even more pressing in the livestock sector, given that "if the world remains on course to roughly double meat and dairy consumption relative to 2000 levels by mid-century, livestock production will continue to industrialize and expand" (Cassou, 2018) and this level of FLW goes directly against the improvements necessary in SCs to deal with the probable future needs of feeding the world.

Some reports in the literature point out the importance that the livestock production plays in the FLW problem (Beretta et al., 2017; Alexander et al., 2017). Even though the environmental impacts of FLW are highest for fresh vegetables, due to the large amounts wasted, the impacts associated with meat products are also extremely important, since the specific impact per kg is largest for beef (Beretta et al., 2017). Livestock production is also associated with the largest rates of mass, energy and protein losses (Alexander et al., 2017). Despite all this, FLW data for meat products in developing countries are still of relatively poor quality when compared to data for developed countries (Spang et al., 2019). This is also true for the Brazilian context, where very little is known about the levels and the causes of FLW.

The FLW problem has been studied for other beef SCs around the world. Jaja et al. (2018) identified the major causes of the rejection of offal and carcasses in abattoirs in South Africa. The UK beef SC was analysed through a value chain analysis technique to develop waste elimination strategies and good management practices, concluding that a philosophy of continuous improvement should be pursued to systematically identify and eliminate the root causes of FLW (Francis et al., 2008). The complaints from consumers via Twitter were evaluated to determine root causes in the British beef SC, evidencing that waste can be generated at one stage of the SC and its cause be linked to another (Mishra and Singh, 2018; Spang et al., 2019). For example, beef that becomes discoloured before its sell-by date and is discarded at retail, might be caused by the lack of vitamin E in the diet fed to the cattle on the beef farms. This seems to support the idea that an analysis focusing on the different stages of the food SC is necessary to fully understand why food products are being discarded and, consequently, assess what can be done to prevent these situations (Martínez et al., 2014; Mena et al., 2014; Vilariño et al., 2017; Spang et al., 2019).

The aim of this research is to improve the discussion concerning FLW in the Brazilian beef SC in three different ways. First, it expands the literature by presenting the main causes of FLW in the context of the Brazilian beef SC. Second, using the ISM methodology, it shows that there is a group of causes with high influence and strategic importance for the reduction of FLW. ISM was chosen due to its reliability to develop hierarchical structures (Malek and Desai, 2019; Xu and Zou, 2020) and its ability to capture dynamic complexities, in comparison with other multi-criteria decision-making approaches (Shahabadkar et al., 2012).

Third, the results from the ISM methodology were complemented with a MICMAC analysis to determine the dependence and driving powers of the causes and thereby identify the root causes of FLW.

Thus, the next section provides a contextualisation of the Brazilian beef SC, which will be the focus of this study. Section 3.3 presents a literature review about the FLW issue. Then, section 3.4 describes the research methodology adopted in this study. Section 3.5 describes the main causes of FLW in the Brazilian beef SC and presents the results from the ISM methodology and from the MICMAC analysis. Section 3.6 discusses the practical implications of the results from section 3.5. Lastly, section 3.7 presents the main conclusions.

3.2. The Brazilian beef SC

Brazil is well-known for being a strong player in the agribusiness global market. Regarding the beef sector, the country stands out for being the second largest producer, with 214.69 million heads of cattle in 2018 (ABIEC, 2019) and the biggest exporter in the world. The value generated by livestock was US$ 188.43 billion[3], i.e. 8.7% of the national GDP, which was also the largest ever recorded in the last ten years (ABIEC, 2019). Besides that, Brazil exported 1.64 million tons, which is the largest volume ever achieved amongst all exporting countries, reaching US$ 6.57 billion (ABIEC, 2019).

Currently, beef production in Brazil is very heterogeneous in terms of size, technology adopted and productivity (ABIEC, 2019). Some production systems have relatively low quality and are based on extensive production, low technological intensity and poor management and marketing standards for cattle. The high-quality ones are based on the adoption of advanced technology and efficient management and marketing standards (Carvalho and Zen, 2017).

Due to the evolution in exports, the increasing demand for high quality beef cuts and the strict legislation, different stakeholders have been working to be more efficient in ensuring animal health, reducing the incidence of outbreaks of disease and controlling product quality (Valdes and Diaz Osorio, 2015). However, there is evidence associated with coordination failures in the Brazilian beef SC. Moita and Golon (2014) and Medeiros et al. (2012), for instance, reported a lack of coordination in the slaughter-producer link. In this relationship, the slaughterer is a price maker due to his/her high market power, promoted by the oligopsonistic market structure that characterizes the Brazilian beef SC (Moita and Golon, 2014). This stakeholder ends up accessing privileged and valuable information, which generates an information asymmetry and in turn leads to a loss of efficiency in the chain (Medeiros et al., 2012). Coordination problems compromise the performance of various agents, especially in relation to quality and health requirements (Caleman et al., 2008). Ensuring animal health also became more pressing in Brazil, since a major part of the loss (in value) is derived from parasitic diseases. The combined annual economic loss due to internal and external parasites of cattle in Brazil is at least US$ 13.96 billion (Grisi et al., 2014). Another concern in the Brazilian beef SC lies in the injuries sustained by cattle during shipping, the transportation of live animals and pre-slaughter handling. The frequency of the injuries varies significantly with the shipping times and the consequent annual economic losses in a midsized slaughterhouse may exceed US$ 63,000 (Polizel Neto et al., 2015). Notwithstanding, in Brazil, beef wastage also exists among the householders due mainly to lifestyle and cultural reasons (Bastos, 2018).

Despite its economic benefits, the Brazilian beef SC has negative social and environmental impacts, which have attracted some attention, particularly concerning: the deforestation of the

[3] Based on the average exchange rate from U.S. Dollars to the Brazilian Real for the year 2017: 3.1694.

Amazon rainforest, emissions of green-house gases and precarious labour conditions (Carvalho and Zen, 2017; Sparovek et al., 2018). Scientific research has also raised some concerns regarding the relationship between the expansion of pasture areas and climate change (Bustamante et al., 2012). As a result, addressing efficiency issues in the beef and infrastructure sector is considered of utmost importance to reduce its environmental impacts and to counteract the effects of the growing production demand (Carvalho and Zen, 2017).

3.3. An Overview of the FLW Problem

The FLW problem has been largely studied in the literature for very different food SCs and for very different contexts, since FLW occurs at all stages of the food SC and its causes are diverse and vary according to the stages of the SC, the regions under study and the food product under analysis (Bräutigam et al., 2014; Magalhães et al., 2019). In general, the literature agrees that in developing countries, FLW is more relevant in the earlier stages of the food SC, due to a lack of infrastructures and technical and managerial skills in food production and transportation, and that in developed countries, FLW is more evident in retail and consumption, mainly because of bad coordination and communication between the stages, as well as the consumers' attitudes (Bräutigam et al., 2014; Balaji and Arshinder, 2016; Schanes et al., 2018).

Combating FLW is not an easy task, especially considering that FLW is not generated by one or even just a few main factors but is the result of an intricate web of extremely diverse and interconnected causes instead (Canali et al., 2017). The fact that these causes are not independent from each other (Mena et al., 2011) also increases the difficulty in combating this issue. Even though many researchers have studied the drivers of FLW (e.g., Mena et al., 2011; Canali et al., 2017), the research is clearly more focused on the supplier and retailer interface (e.g., Mena et al., 2011) and on the consumer stage (e.g., Özbük and Coşkun, 2019) of the food SC, often using data from the literature, instead of supporting the results on practical or industrial data (Priefer et al., 2016), and the results are often not comparable (Emana et al., 2017). Also, these studies usually list the causes of FLW in particular contexts or classify them according to their nature (e.g., Mena et al., 2011), but the analyses lack depth, since there is a lack of understanding of the interrelatedness between the causes and which are more influential in terms of FLW. Understanding the causes of FLW is fundamental to guide the implementation or the design of effective measures to prevent or mitigate FLW along the food SC appropriately (Priefer et al., 2016).

Some authors have used multi-criteria decision-making (MCDM) tools to evaluate the relationships between different causes of FLW and establish priorities between them, showing the potential of these multidimensional approaches to investigate the FLW issue. For instance, Gardas et al. (2017), Balaji and Arshinder (2017) and Gardas et al. (2018) used the ISM methodology, the

Total Interpretive Structural Modelling approach and the Decision Making And Trial Evaluation Laboratory method (DEMATEL), respectively, to identify, model and determine the key causes of post-harvest losses in the Indian fruit and vegetable SC. Raut et al. (2018) used the Analytic Hierarchy Process (AHP) to identify the causes of FLW in the Indian fruit and vegetable SC and rank them by their relative importance. Mishra et al. (2017) studied the beef products and identified the factors influencing the consumer's beef purchasing decisions, assessing their interrelationships using the ISM methodology. ISM seems to be suitable to model the relationships between the causes of FLW. The AHP methodology assumes that the criteria are independent, failing to consider their interactions and dependencies (Gardas et al., 2018). The DEMATEL methodology is a micro approach that uses Likert scales to evaluate the strength of the relationships (Kumar and Dixit, 2018), making it more difficult to implement than ISM, despite showing very similar results to the ones from the ISM methodology (Chauhan et al., 2018). Moreover, the ISM methodology does not require knowledge regarding the level of dominance to establish the interrelation between the causes of FLW (Gardas et al., 2017).

In sum, there are few existing studies examining the relationships between the causes of FLW systematically, particularly within the context of the Brazilian beef SC. Thus, this paper contributes to the body of knowledge regarding FLW in the Brazilian beef SC, by developing a three phase methodology to: identify the relevant causes of FLW, assess their interrelatedness from an SC perspective and determine the root causes of FLW in the Brazilian beef SC. The methodology developed can be used as the starting point for setting FLW mitigation strategies.

3.4. Research Methods

The three-phase methodology in Figure 3.1 was adopted to achieve this study. The framework consists of three distinct phases. In the first phase, a literature review was performed to identify the causes of FLW in the beef SC. In the second phase, the causes representative of the Brazilian beef SC were recognized and the hierarchical structure of the causes was established, using the ISM methodology. In the third phase, the MICMAC analysis classified the causes according to their driving and dependence power and determined the root causes of FLW in the Brazilian beef SC.

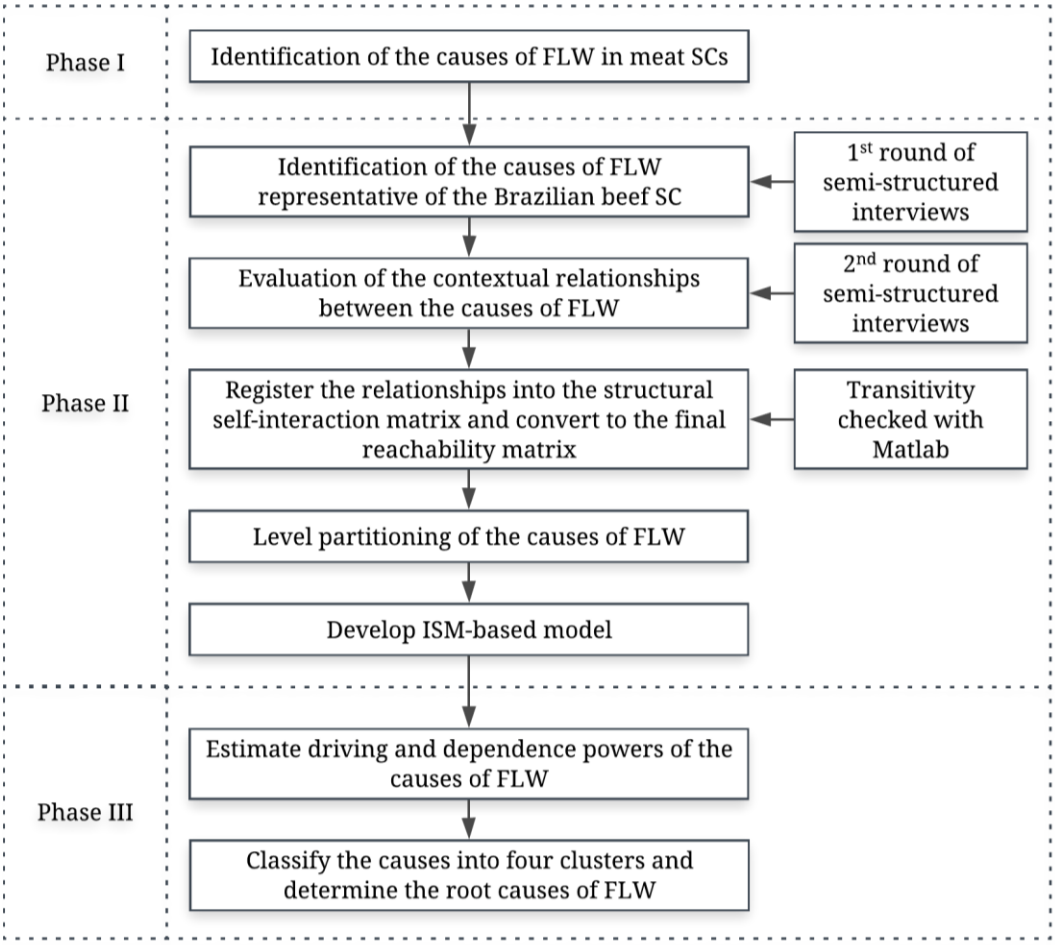

Figure 3.1 – Methodology framework.

3.4.1 Phase I

In the first phase of our study, a literature review was performed, to search and review literature related to beef SCs, in order to identify the main causes of FLW. Keywords such as: "cause", "beef", "supply chain", "food loss and waste" or other waste related terms, like "food waste", "food loss" and "food wastage" were used to search for relevant literature in the Web of Science database and in Google Scholar. However, due to the scarcity of information for beef SCs, the authors of the present paper decided to review the more generic meat SCs instead, replacing the keyword "beef" by the generic keyword "meat". The results from this literature review are presented in section 3.5.1. Despite broadening the focus of the literature review from beef to more general "meat" SCs, the focus of this paper and the analysis herein performed concerns the beef SC, since the experts interviewed are part of the Brazilian beef SC (see the next sub-section for more details).

3.4.2 Phase II

In the second phase of our study, ISM methodology was used to identify and assess the interrelationships between the causes of FLW throughout the Brazilian beef SC, presenting a graphical structural map of the causes and the connections between them and highlighting the most critical causes influencing the generation of FLW.

ISM is a technique that evaluates if and how the variables of a complex problem are related, based on the judgement of experts. Those judgements will allow ISM to hierarchize the relationships between the variables and translate unclear mental models into visible and well-defined systems (Kwak et al., 2018). Three different MCDM techniques are applied in the literature to develop structural hierarchies: Fuzzy Cognition Map (FCM), DEMATEL and ISM. However, FCM and DEMATEL have clear limitations over the ISM methodology. On one hand, FCM requires hard optimisation of all the membership functions' parameters and can converge in an undesired steady-state. On the other hand, DEMATEL determines the ranking of alternatives based on their dependency, but does not consider all criteria, and the relative weights of experts are not aggregated to personal decisions of experts within the group assessments (Malek and Desai, 2019). ISM overcomes these limitations by classifying the complex problem into various groups, which individually represent a segment of the complex problem. This is achieved through practical experience and the knowledge of the experts. ISM provides insight into the interrelationships among different variables, but also helps to find the hierarchical way those variables are organised, determining the order and direction on the complexity of relationships among the variables of the complex system (Xu and Zou, 2020). This makes ISM the most preferred and reliable approach for the development of the hierarchy structural model (Malek and Desai, 2019; Xu and Zou, 2020). Moreover, ISM is capable of capturing dynamic complexities, while other multi-criteria decision-making methodologies have trouble representing real-life complex problems and less ability to capture dynamic behaviours (Shahabadkar et al., 2012). ISM has been recently adopted in the field of SC management to model, for example, the risk factors in international SCs (Kwak et al., 2018) and the causes of FLW in the Indian fruit and vegetable SC (Gardas et al., 2017). Therefore, based on the above discussion, ISM is the chosen methodology to be applied in this study.

The studies of Shen et al. (2016), Kwak et al. (2018) and Gan et al. (2018) were used to guide the implementation of ISM. Based on those works, the steps to implement ISM are as follows. First, one must identify and list the variables comprising the system to be studied. Second, the contextual relationships must be identified by experts among each pair of variables and registered into a Structural Self-Interaction Matrix (SSIM). Then, the SSIM is translated into an initial reachability matrix (IRM), which is a binary matrix that represents the direct relationships between the variables. This matrix will be checked for transitivity to also capture the indirect links between variables and will be transformed into the final reachability matrix (FRM) that will then account for all the relationships (direct and indirect) between the variables. After computing the FRM, level partitioning is applied, arranging the elements according to their levels. Afterwards, the ISM-based model is drawn up by connecting the variables at each level, based on their relationships from the IRM. Finally, the ISM-based model is presented to experts to ascertain its consistency.

To implement the ISM methodology, semi-structured interviews were conducted with a set of experts on FLW in the Brazilian beef SC and were guided by at least two of the authors to eliminate bias related to the acknowledgement of the experts' arguments and opinions. The experts were recruited based on their years of experience (over 10 years) in the Brazilian beef sector. A total of 15 experts were contacted and 7 agreed to be a part of this study. Their profiles are presented in Table 3.1. All experts have extensive knowledge on FLW in the Brazilian beef SC and the combined group of experts have experience from production until retail, including export, ensuring a holistic view of the beef SC. The previous literature does not establish the minimum number of experts to successfully implement ISM. However, meaningful results can be obtained when well-developed selection criteria are used for sampling (Gan et al., 2018) and the number of experts does not have to be big, it can be as few as two, so long as the experts interviewed are qualified on the subject under study (Shen et al., 2016). Therefore, the authors assume that interviewing seven experts is adequate, even though subjectivity is unavoidable. The opinions of the experts were only considered when the majority, i.e. four or more experts, were in agreement, following the recommendations of Shen et al. (2016), to ensure consensus.

Table 3.1 – Profile of the experts.

Expert	Working organisation	Role in the organisation
1	Agribusiness research institute	Senior Consultant
2	Large scale producer	Chief Executive
3	Small scale producer	Chief Executive
4	Slaughterhouse and livestock machinery manufacturer	Senior Operations Manager
5	Software company - food traceability and management systems	Chief Executive
6	Department of Agribusiness Engineering in a Brazilian University	Associate Professor
7	Brazilian Agricultural Research Corporation (Embrapa)	Consultant

The expert intervention in this research happened at two different moments. First, semi-structured interviews, lasting from 90 to 120 minutes, were conducted with each expert to discuss the causes of FLW in the beef SC in Brazil. The experts received an e-mail beforehand with the list of causes of FLW encountered in the literature for meat SCs (see section 3.5.1), and were asked to confirm and agree on the definition of the causes and their suitability for the context of the Brazilian beef SC. Furthermore, they were also invited to list other causes. Second, the experts were later invited to a second semi-structured interview to judge the relationships amongst the causes under study. After implementing the ISM methodology, the hierarchical structure was sent via e-mail to the experts and ad hoc contacts were made with some of the experts to ensure the consistency of the results and to collect any additional information.

3.4.3 Phase III

In the third and final phase of our study, the Matrix Impact of Cross Multiplication Applied to Classification (MICMAC) analysis was used to evaluate the repercussion that an impact on a variable would have on the whole system (Gan et al., 2018). The MICMAC analysis is usually performed after the ISM methodology and analyses the driving and dependence powers of each variable (Shen et al., 2016).

The driving power of a variable indicates the capacity that it has to influence other variables in the system and the dependence power indicates the degree to which it is influenced by the other variables. A driving-dependence power diagram is consequently constructed, and the variables are classified into four different clusters: (1) Autonomous, (2) Dependent, (3) Linkage and (4) Independent. The most important cluster to this research is the independent one, which includes the causes that have strong driving, but weak dependence power. Since these causes influence the majority of the others, but are almost not influenced by any of them, they are considered the root causes of the problem.

3.5. Results

3.5.1 Causes of food loss and waste in meat SCs (Phase I)

A literature review was performed in this study to search and review relevant literature on the causes of FLW in meat SCs. The literature review was also useful to set definitions for each cause. This information was crucial to guide the semi-structured interviews with the experts. The main causes of FLW in meat SCs are described below.

1. **SC inefficiencies:** Taylor (2005) identified some issues related to the management and control of the SC that influence the levels of FLW. If an SC is too fragmented and no one has responsibility for its management in its entirety, then no one can be accountable for, for example, the sub-optimal inter-company transport policies. This fragmentation leads to a lack of trust and to hostile behaviour between the different stages of the SC. Furthermore, a lack of coordination and information sharing between stages can lead to overstocking and consequently contribute to FLW (Kaipia et al., 2013; Buisman et al., 2019).

2. Cold chain inefficiencies: Maintaining cold chain integrity, from production until the product reaches the shelves of supermarkets, is crucial to maintain the product's quality above a certain threshold. Cold chain interruptions, due to mishandlings of the product or to a lack of refrigerated carriers during transportation, lead to the deterioration of the product's quality, which could spoil the product before the use-by date is reached (Rossaint and Kreyenschmidt, 2015). The improper management of the cold chain also increases the risk of microbial hazards, which may lead to food-borne diseases (Shashi et al., 2018).

3. Lack of transportation infrastructures: Kaipia et al. (2013) showed that a faster transportation had the potential to improve the remaining shelf life of a product at the retailer, supporting the fact that an underdeveloped or aging transportation infrastructure limits the movement of products between the SC stages and contributes to the generation of FLW (Cassou, 2018). Bad weather conditions can also compromise the use of roads in certain regions, particularly in developing countries, leading to losses in-transit (Francis et al., 2008). These losses also depend on the distance and the total time of the transport, on the means and density of transport, and on the conditions regarding handling and facilities (Miranda-de la Lama et al., 2014; Mendonça et al., 2018). The deficiency of infrastructure is also one of the main reasons why firms avoid investing in cold chains, since it prevents their efficient management (Gligor et al., 2018).

4. Inadequate handling: The bad or rough handling and the direct contact of products with the operators lead to mechanical damage and microbial contaminations, resulting in early spoilage and contributing to the generation of FLW (Francis et al., 2008; Rossaint and Kreyenschmidt, 2015; Krajewski and Swiatkowska, 2018). The microbial contamination accelerates on the product's surface once the different meat cuts are prepared (Jeyamkondan et al., 2000).

5. Inadequate packaging: Inadequate packaging contributes to the generation of FLW. The design and the material of the packaging and the atmosphere, in which the product is kept, influence the mechanical damage and the microbial contaminations suffered by the product, conditioning the product's quality. This will have an influence on the levels of FLW (Buzby et al., 2009; Zhang et al., 2015; Henz and Porpino, 2017; Krajewski and Swiatkowska, 2018), on the product's cost and on its shelf life (Jeyamkondan et al., 2000). If the packaging compromises the products' shelf life, it will also compromise transport over long distances which, in turn, also promotes FLW (Jeyamkondan et al., 2000).

6. Poor operational performance: Poor operational performance influences the level of FLW and relates to problems in the processing and cutting of meat products, due to the misuse or malfunction of machines and the poor hygiene and sterilisation of tools and other utensils. These lead to the deterioration of the product's quality and compromise the cuts of meat (Francis et al., 2008).

7. Discounting strategies: Discount policies and the management of promotions have an impact on the levels of FLW, especially at the retail level, since they induce variability in the consumer demand. This variability creates unexpected uncertainties in the number of products sold, which will influence the generation of FLW (Kaipia et al., 2013; Buisman et al., 2019).

8. Inadequate demand forecasting: The inadequacy of the demand forecasting models is a major factor influencing FLW. Stakeholders along the SC do not openly share data or adopt advanced forecasting techniques, which lead to a mismatch between the animal breeding and the real consumer demand (Taylor, 2005; Kaipia et al., 2013; Buisman et al., 2019).

9. Inventory management strategies: The inventory management influences the generation of FLW, particularly in retail. The minimum order size and the product's turnover impact on the availability of the product and the time it stays on the shelf of the supermarket, leading to products being left unsold (Eriksson et al., 2016).

10. Variety of products available in supermarkets: The variety of the products available in-store contributes to the generation of FLW (Buzby et al., 2009). Consumers are continuously seeking new tastes, different cuts and more convenient options, increasing the number of meat products offered by the retailer, which will increase the variability of the demand and require more in-store effort to manage inventory and shelf space, leading to higher FLW levels.

11. Sensory or biochemical deterioration: Major quality defects due to the sensory or biochemical deterioration contribute to the rejection of meat products, causing FLW along the SC. These rejections are due to changes mainly in colour, texture, flavours or odour of the meat products (Zhang et al., 2015; Krajewski and Swiatkowska, 2018).

12. Short remaining shelf lives: Short remaining shelf lives contribute to the generation of FLW, since these products are more likely to be left unsold. The fact that stakeholders still make decisions along the SC based on fixed shelf lives also aggravates this problem (Kaipia et al., 2013; Eriksson et al., 2016; Buisman et al., 2019).

13. End of expiry date before sale: Another cause of FLW is when products reach the end of the expiry date before being sold, even if the product is still edible (Kaipia et al., 2013; Rossaint and Kreyenschmidt, 2015; Eriksson et al., 2016). This happens sometimes due to the consumers' misunderstanding of "use by" and "best before" dates (Zhang et al., 2015).

14. Lack of quality monitoring throughout the SC: The decisions made along the SC, regarding the route a product takes until it reaches the supermarket shelf, can greatly influence the levels of FLW. The temperature history of a product (to see if any temperature abuse took place previously) is not yet visible along the SC, which limits the efficiency of the decision making along the SC. This can result in meat products reaching supermarket shelves too late (Rossaint and Kreyenschmidt, 2015; Buisman et al., 2019), with reduced product quality (Shashi et al., 2018).

15. Non-conformance to quality or safety requirements: Meat products that do not meet the quality or safety requirements imposed by the market, for weight or fat percentages, are rejected (Taylor, 2005; Francis et al., 2008; Rossaint and Kreyenschmidt, 2015).

16. Microbial or chemical spoilage: Deterioration of product quality due to microbial or chemical contaminations by exposure to inadequate temperature or humidity during transport or by the mishandling of operators (e.g. lack of hygienic care) can cause meat products to be discarded (Francis et al., 2008; Falowo et al., 2014; Zhang et al., 2015).

17. Unhealthy animals due to diseases: Unhealthy and unwholesome meat are a cause of FLW. This meat is removed from the SC to protect the consumers and to help eradicate certain diseases (Jaja et al., 2018).

18. Organ condemnation: Another cause of FLW, particularly in abattoirs, is the condemnation of animal organs, due to the presence of abscesses, bruises or inflammation, without rejecting the whole carcass (Jaja et al., 2018).

19. Outbreak of foodborne diseases: The outbreak of foodborne diseases often leads to the rejection of animals during breeding, generating FLW (Falowo et al., 2014).

20. Performance indicators not focused on waste levels: Taylor (2005) concluded that establishing key performance indicators is crucial to drive improvements in the SC performance, and, concerning this, Kaipia et al. (2013) find that using performance indicators focused only on cost, efficiency, and availability is another cause of FLW in meat SCs. Availability has had greater importance than FLW related indicators until now.

3.5.2 ISM Methodology (Phase II)

Identification of the causes of food loss and waste in the Brazilian beef SC

Semi-structured interviews were conducted with the experts to identify the causes of FLW in the Brazilian beef SC. The experts were invited to judge which causes gathered from the literature, and listed in section 3.5.1, are representative of the context of the Brazilian beef SC and therefore should be considered in this study. In order to guide the interviews, the authors conducting each interview asked the experts a set of previously defined questions:

- Are there any causes not applicable to the beef SC in Brazil? If so, which ones should be ignored?
- Are the definitions clear and appropriate? If not, what should be changed?
- Are there any similarities between the causes? If so, which ones should be integrated?
- Are there any other causes not considered? If so, which ones should be included?

After collecting the responses from all interviewees, the research team carefully analysed the experts' feedback to select the relevant causes of FLW. A cause was only selected when the majority of the experts, i.e., when four or more experts, agreed upon its applicability in the Brazilian beef SC. As a result, 16 causes of FLW emerged and are listed in Table 3.2. The table also shows how the causes were selected. Twelve causes (C1 to C9, C12, C13 and C15) were directly selected from the list presented in section 3.5.1. However, the process to select the other four was different. The majority of the experts agreed that C11, C12 and C14 should be a fusion of two different causes from the literature (from section 3.5.1), since they had very similar consequences and behaviours in the Brazilian beef SC. Additionally, five of the seven experts also agreed that there was another cause of FLW visible in the Brazilian beef SC that was not considered in previous literature. That cause is the lack of standardisation of the different cuts of beef (C16), which influences the meat cutting and may lead to unnecessary trims and FLW. If the cuts of beef are different to what is expected by retailers or consumers, it can also compromise the sale of such cuts.

Table 3.2 – Causes of FLW in the Brazilian beef SC

Nr.	Cause	Nr. in section 3.5.1	Referred to by
C1	SC inefficiencies	1	Taylor (2005); Kaipia et al. (2013); Buisman et al. (2019)
C2	Cold chain inefficiencies	2	Rossaint and Kreyenschmidt (2015); Gligor et al. (2018)
C3	Lack of transportation infrastructures	3	Francis et al. (2008); Kaipia et al. (2013); Miranda-de la Lama et al. (2014); Cassou (2018); Gligor et al. (2018); Mendonça et al. (2018)
C4	Inadequate handling	4	Jeyamkondan et al. (2000); Francis et al. (2008); Rossaint and Kreyenschmidt (2015); Krajewski and Swiatkowska (2018)
C5	Poor operational performance	6	Francis et al. (2008)
C6	Discounting strategies	7	Kaipia et al. (2013); Buisman et al. (2019)
C7	Inadequate demand forecasting	8	Taylor (2005); Kaipia et al. (2013); Buisman et al. (2019)
C8	Inventory management strategies	9	Eriksson et al. (2016)
C9	Variety of products available in supermarkets	10	Buzby et al. (2009)
C10	Quality (sensorial or microbial) deterioration	11 + 16	Falowo et al. (2014); Zhang et al. (2015); Francis et al. (2008); Krajewski and Swiatkowska (2018)
C11	Short remaining shelf life or expired products	12 + 13	Kaipia et al. (2013); Rossaint and Kreyenschmidt (2015); Zhang et al. (2015); Eriksson et al. (2016); Buisman et al. (2019)
C12	Lack of quality monitoring along the SC	14	Rossaint and Kreyenschmidt (2015); Shashi et al. (2018); Buisman et al. (2019)
C13	Non-conformance to quality or safety requirements	15	Taylor (2005); Francis et al. (2008); Rossaint and Kreyenschmidt (2015)
C14	Unhealthy animals and outbreaks of disease	17 + 19	Falowo et al. (2014); Jaja et al. (2018)
C15	Organ condemnation	18	Jaja et al. (2018)
C16	Lack of standardisation of the different cuts of beef		Mentioned by 5 of the experts

Structural self-interaction, initial and final reachability matrices

The experts were then invited for a second interview to make the pair-wise comparisons of the 16 causes of FLW by answering the question "Does cause i directly influence cause j?". The 16 causes generated 120 (16 times 15, divided by 2) pair-wise comparisons. To capture and analyse the relationships between the causes, four letters were used to represent the direction of the relationship between each pair of causes. Letter V means that cause i influences cause j; letter A means that cause j influences cause i; letter X means that causes i and j influence each other; and letter O means that causes i and j are unrelated. However, different experts may judge the pair-wise comparison of two causes differently. Therefore, in this research, the contextual relationships among the causes was determined by the rule suggested by Shen et al. (2016), that "the minority gives way to the majority". The interrelationships between the causes of FLW in the Brazilian beef SC are represented in Table 3.3.

Table 3.3 – Structural Self-Interaction Matrix

C[i/j]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	-	O	O	O	O	A	A	A	A	O	O	V	O	O	O	O
2		-	A	A	O	O	O	O	O	V	V	A	V	O	O	O
3			-	O	O	O	O	O	O	V	V	O	V	O	O	O
4				-	X	O	O	O	O	V	O	O	O	O	O	O
5					-	O	O	O	O	V	V	O	V	O	O	O
6						-	X	X	A	O	A	A	O	O	O	O
7							-	V	A	O	O	O	O	A	O	O
8								-	A	O	V	O	O	O	O	O
9									-	O	O	O	O	O	O	V
10										-	V	A	V	O	O	O
11											-	O	O	O	O	O
12												-	O	O	O	O
13													-	O	A	O
14														-	O	O
15															-	O
16																-

Note: C[i/j] represents the cause in line i or in column j.

Table 3.3 demonstrates the direct relationships among the causes of FLW. After that, the previous matrix is converted into the IRM, by substituting V, A, X and O with 1's and 0's, transforming SSIM into a binary matrix, following the rules:

- If the (i, j) entry in the SSIM is V, then the (i, j) entry in the IRM becomes 1 and the (j, i) entry becomes 0;
- If the (i, j) entry in the SSIM is A, then the (i, j) entry in the IRM becomes 0 and the (j, i) entry becomes 1;
- If the (i, j) entry in the SSIM is X, then the (i, j) and (j, i) entries in the IRM become 1;
- If the (i, j) entry in the SSIM is O, then the (i, j) and (j, i) entries in the IRM become 0.

The IRM was subsequently checked for transitivity with a Matlab routine to avoid human error. In sum, if cause i is directly related to cause j and cause j is directly related to cause k, then causes i and k are indirectly related, by means of the cause j, and if the entry (i, k) of the IRM was 0, then it must be replaced by a 1*. This transforms the IRM into the FRM (see Table 3.4) that accounts for all relationships between the causes (direct and indirect). Driving and dependence powers were calculated using the latter matrix, but their purpose for the MICMAC analysis will be explained in section 3.5.3.

Table 3.4 – Final reachability matrix

C[i/j]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	DVP
1	1	1*	0	0	0	1*	0	0	0	1*	0	1	0	0	0	0	5
2	0	1	0	0	0	1*	0	0	0	1	1	0	1	0	0	0	5
3	1*	1	1	0	0	1*	1*	1*	0	1	1	0	1	0	0	0	9
4	1*	1	0	1	1	1*	1*	1*	0	1	1*	0	1*	0	0	0	10
5	1*	1*	0	1	1	1*	1*	1*	0	1	1	0	1	0	0	0	10
6	1	1*	0	0	0	1	1	1	0	1*	1*	1*	1*	0	0	0	9
7	1	1*	0	0	0	1	1	1	0	1*	1*	1*	1*	0	0	0	9
8	1	1*	0	0	0	1	1*	1	0	1*	1	1*	1*	0	0	0	9
9	1	1*	0	0	0	1	1	1	1	1*	1*	1*	1*	0	0	1	11
10	0	0	0	0	0	1*	0	0	0	1	1	0	1	0	0	0	4
11	1*	1*	0	0	0	1	1*	1*	0	1*	1	1*	1*	0	0	0	9
12	1*	1	0	0	0	1	1*	1*	0	1	1*	1	1*	0	0	0	9
13	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
14	1*	1*	0	0	0	1*	1	1*	0	1*	1*	1*	1*	1	0	0	10
15	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	2
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
DPP	11	12	1	2	2	13	10	10	1	13	12	8	14	1	1	2	

Note: C[i/j] represents the cause in line i or in column j; DPP – Dependence Power; DVP – Driving Power.

Level partitioning

After developing the FRM, level partitioning was performed. For each cause, the reachability set, the antecedent set and the intersection set were found, to assess the levels of influence of each cause. The reachability set of cause i includes all causes that are influenced by cause i (which are represented by 1s in the row of the FRM corresponding to cause i), the antecedent set of cause i includes all causes that influence cause i (which are represented by 1s in the column of the FRM corresponding to cause i) and the intersection set comprises the common causes found in both the reachability and antecedent sets. When the intersection set is equal to the reachability set of a certain cause, then that cause is attributed to the level of that iteration. The causes assigned to one level are then removed from the remaining reachability and intersection sets for the next iteration and the same process is applied until all the causes are partitioned into levels.

Table 3.5 illustrates the level partitioning results of the 16 causes of FLW in the Brazilian beef SC. Five causes (C3, C4, C5, C9 and C14) have the same reachability and antecedent set in the first iteration, comprising the first level of the ISM-based model. After removing these from the reachability and intersection sets of the remaining causes for the second iteration, then the next causes with the same reachability and antecedent sets are C6, C10 and C15. After six iterations, all causes were partitioned into levels and the ISM-based model can be depicted.

Table 3.5 – Level partitioning results

Causes	Reachability set	Antecedent set	Intersection set	Level
1	1,12	1,3,4,5,6,7,8,9,11,12,14	1,12	4
2	2,11	1,2,3,4,5,6,7,8,9,11,12,14	2,11	3
3	3	3	3	6
4	4,5	4,5	4,5	6
5	4,5	4,5	4,5	6
6	1,2,6,7,8,10,11,12	1,2,3,4,5,6,7,8,9,10,11,12,14	1,2,6,7,8,10,11,12	2
7	7,8,11	3,4,5,6,7,8,9,11,12,14	7,8,11	5
8	7,8,11	3,4,5,6,7,8,9,11,12,14	7,8,11	5
9	9	9	9	6
10	6,10,11	1,2,3,4,5,6,7,8,9,10,11,12,14	6,10,11	2
11	7,8,11	2,3,4,5,6,7,8,9,10,11,12,14	7,8,11	5
12	1,7,8,11,12	1,6,7,8,9,11,12,14	1,7,8,11,12	4
13	13	2,3,4,5,6,7,8,9,10,11,12,13,14,15	13	1
14	14	14	14	6
C15	15	15	15	2
C16	16	9,16	16	1

ISM-based model

A direct graph, or digraph, is built by arranging the causes vertically according to the level partitioning (Table 3.5) and by connecting the causes according to the IRM, i.e. if cause i influences directly cause j (meaning that if the entry (i, j) of the IRM equals 1), then an arrow is used, pointing from i to j, to show the direct influence between these two causes. The ISM-based model, shown in Figure 3.2, demonstrates the hierarchical structure of the causes of FLW in the Brazilian beef SC and highlights their interrelationships.

Figure 3.2 shows six different levels of influence. The first level of the ISM-based model is comprised by the non-conformance to quality or safety requirements (C13) and the lack of standardisation of the different cuts of beef (C16). The second level directly influences the first level and is comprised by the discounting strategies (C6), the quality (sensorial or microbial) deterioration (C10) and the organ condemnation (C15). The third level directly influences the second level and comprises the cold chain inefficiencies (C2). The fourth level of the ISM-based model directly influences the third and the second level and includes the SC inefficiencies (C1) and the lack of quality monitoring along the SC (C12). The fifth level includes the inadequate demand forecasting (C7), the inventory management strategies (C8) and the short remaining shelf life or expired products (C11) and directly influences the fourth level. Finally, the sixth and final level of the ISM-based model directly influence the fifth level and have the most influence over the other causes considered, comprising the lack of transportation infrastructures (C3), the inadequate handling (C4), the poor operational performance (C5), the variety of products available in supermarkets (C9) and the unhealthy animals and outbreaks of disease (C14).

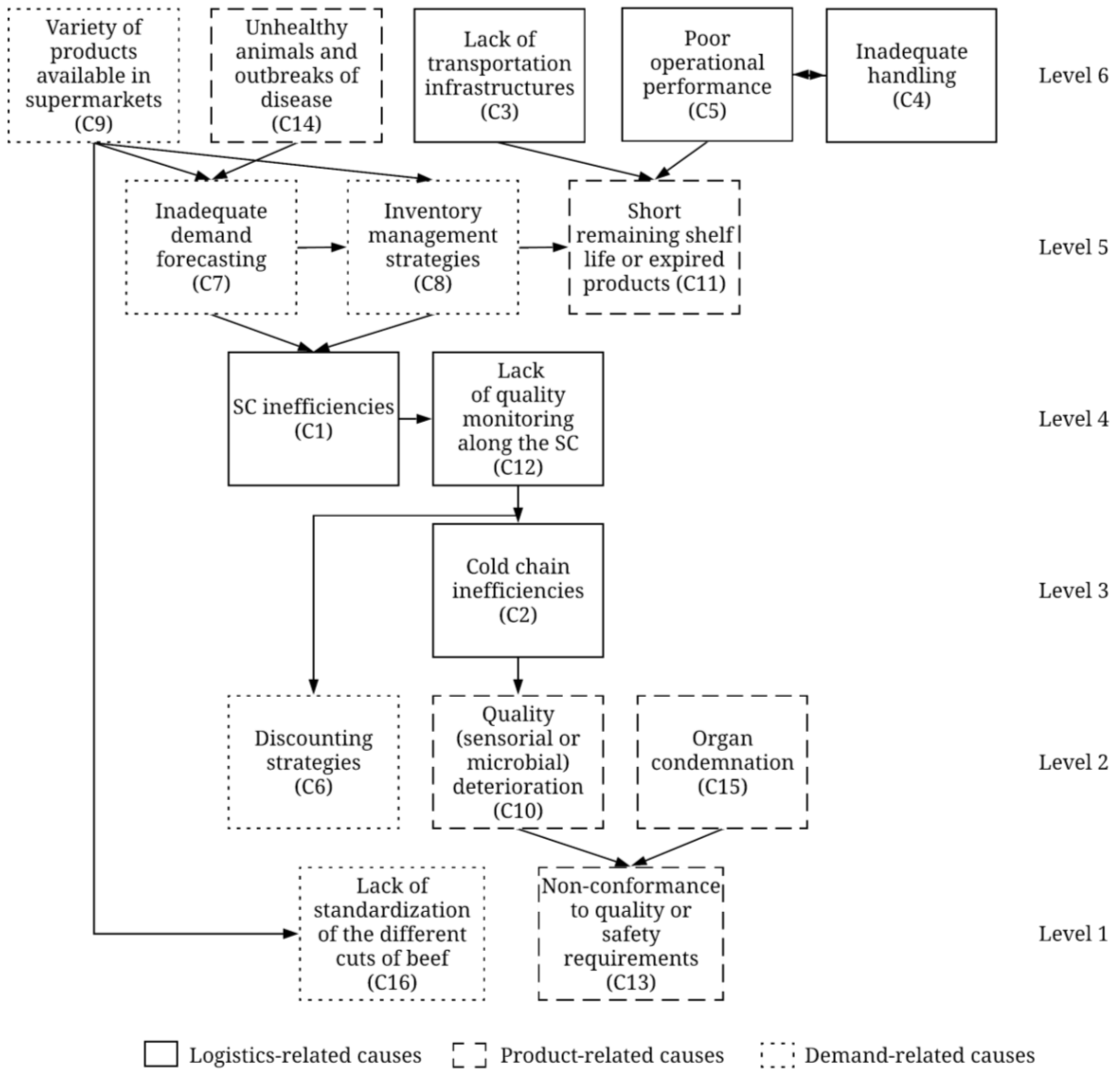

Figure 3.2 – The ISM-based model of the causes of food loss and waste in the Brazilian beef SC.

3.5.3 MICMAC Analysis (Phase III)

The driving and the dependence power for each of the sixteen causes under analysis are shown in Table 3.4. Every 1 in the rows of the FRM indicates which causes are influenced by the cause represented in each row. Therefore, the sum of the rows determines the driving power of each cause. The dependence power is calculated by the sum of the columns of the FRM, since every 1 in the columns of Table 3.4 indicates which causes influence the cause represented in each column. As a result, a driving-dependence power diagram is constructed, and the causes are classified into four clusters, as shown in Figure 3.3.

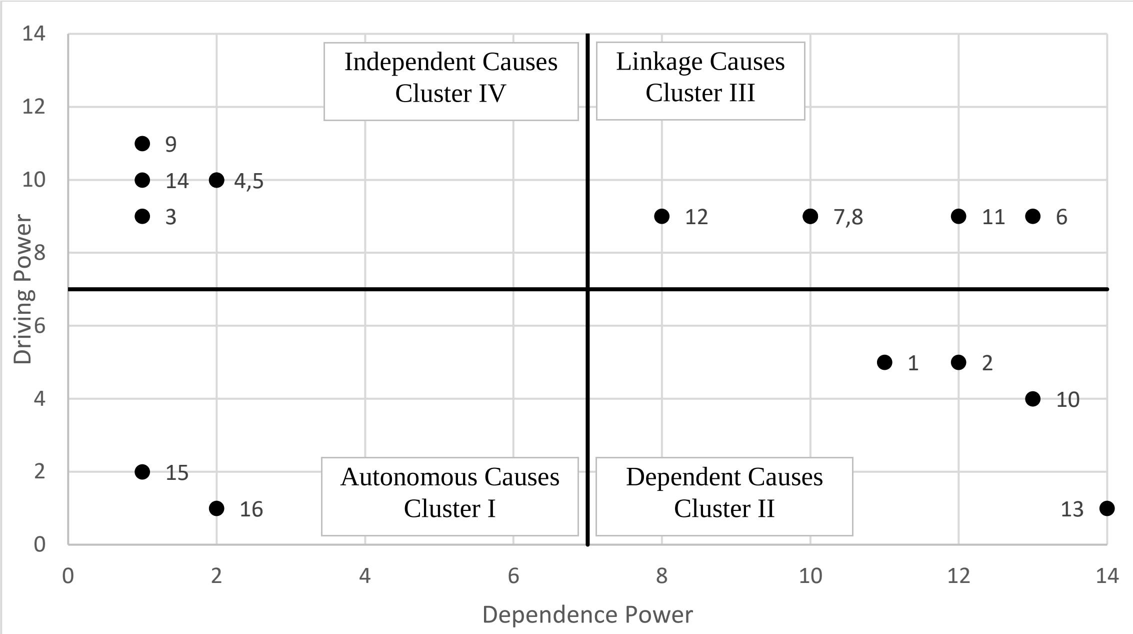

Figure 3.3 – Driving and dependence power of the causes of food loss and waste.

The diagram shows that organ condemnation (C15) and the lack of standardisation of the different cuts of beef (C16) are autonomous causes. These have weak driving and dependence powers and have little influence over the other causes of the FLW investigated, meaning that they are relatively disconnected from the system.

SC inefficiencies (C1), cold chain inefficiencies (C2), quality (sensorial or microbial) deterioration (C10) and non-conformance to quality or safety requirements (C13) comprise the dependent cluster and have weak driving and strong dependence power. These causes are strongly influenced by the other causes of FLW considered, but do not have a significant capacity to influence the other causes. Actions taken concerning the other causes of FLW, will also have an effect on these.

The linkage cluster is characterized by strong driving and dependence powers and includes discounting strategies (C6), inadequate demand forecasting (C7), inventory management strategies (C8), short remaining shelf life or expired products (C11) and lack of quality monitoring along the SC (C12). These causes are quite unstable, since any action concerning them will have an effect on the others, but also a feedback effect on themselves too, which means that they are highly influential on the others, but also strongly influenced by them, making it difficult to assess whether tackling them would be beneficial or not for the whole system.

The fourth and final cluster, representing the independent causes, is characterized by strong driving and weak dependence power, and includes lack of transportation infrastructures (C3), inadequate handling (C4), poor operational performance (C5), variety of products available in supermarkets (C9) and unhealthy animals and outbreaks of disease (C14). These causes influence the majority of the others, but are almost not influenced by any of them, which is why they are considered the root causes of FLW in the Brazilian beef SC.

3.6. Discussion

The six levels of causes of FLW shown in the ISM-based model from Figure 3.2 provide an understanding of their influence in the generation of FLW in the Brazilian beef SC. According to the ISM methodology, corrective actions that mitigate the causes from level 2 will also help to mitigate the causes from level 1. Since the hierarchy has six different degrees of influence, corrective actions taken at levels 1 or 2 will have little to no repercussion at higher levels. Hence, practitioners and stakeholders from the Brazilian beef SC need to pay special attention to the causes from level 6, when designing measures to mitigate FLW, since these will not only counteract those causes, but also help to mitigate the causes from other levels too. Figure 3.3 also conveys the importance of these causes, since they belong to the independent cluster of the MICMAC analysis and are, therefore, considered the root causes of FLW in the Brazilian beef SC.

A new cause of FLW, not previously considered in the literature, was identified by the experts in our study: a lack of standardisation of the different cuts of beef (C16). Even though this cause has no influence over the others, it is directly influenced by the variety of products available in supermarkets (C9), which is a cause with major influence over the generation of FLW in the Brazilian beef SC.

From the assessment of the ISM-based model, it became clear that the causes of FLW can have different natures. C1, C2, C3, C4, C5 and C12 are clearly related to logistical constraints. C6, C7, C8, C9 and C16 are linked to the product demand and to the consumers’ expectations. C10, C11, C13, C14 and C15 are dependent on the intrinsic characteristics of beef products. This division is portrayed in Figure 3.2, where the causes of FLW are divided into logistics-related, demand-related and product-related causes. The root causes of FLW, comprising the sixth level of the ISM-based model, are mostly composed of logistics causes (C3, C4 and C5), but also have one cause related to demand (C9) and another related to the product (C14).

Some of our root causes have already been pointed out as serious challenges to overcome and have been investigated in the literature, supporting the consistency of our model. Even though these studies are not focused on FLW, per se, they have already provided some insights towards what is causing FLW in particular scenarios or contexts and how these issues can be mitigated. A couple of studies have addressed unhealthy animals and outbreaks of disease, by assessing the economic losses due to diseases in cattle, particularly parasitic diseases (Grisi et al., 2014; Rodríguez-Vivas et al., 2017). Other studies have focused on the inadequacy of the handling and transportation infrastructures leading to cattle injuries and bruises at the farm and during the shipping, transporting of live animals and pre-slaughter handling (Polizel Neto et al., 2015; Mendonça et al., 2018), with Miranda-de la Lama et al. (2014) defending the need to improve logistics that prioritise animal welfare and to convince the meat industry and consumers that the ethical value of a product has growing economic importance and can be a business opportunity. Mena et al. (2014) studied the causes of FLW across the food networks of different food products in different UK SCs and concluded that the causes fell into two groups. One relating to supply, including issues with forecasting and planning, promotions management, availability and inventory management, and another relating to the quality of the product and process, including issues with the product's specifications, process controls, shelf life management and packaging and labelling. The group of causes related to supply has common points with this paper's demand-related causes (with issues relating to forecasting, discounting and inventory management). Deep down, these common causes are a consequence of the mismatch between supply and demand, which is why they were classified as supply-related causes in Mena et al. (2014) and as demand-related causes in this paper. The group related to the quality of the product and process also has common points with this paper's product-related causes (with issues relating to the products' shelf life and the quality requirements). However, this paper has also identified a group of causes relating to aspects of the logistics of the beef SC.

The logistics-related causes are more present at the upper levels of the ISM-based model (not belonging to levels 1 and 2), stressing the major influence these causes have on the generation of FLW. Consequently, it is not surprising that some researchers have also addressed these issues. Pimenta et al. (2016) studied the integration between the logistics and marketing functions in Brazilian organisations and showed that this integration can improve the performance of the supply chain, since activities like demand planning, delivery planning and new product development are dependent on information arising from both functions. Knoll et al. (2016) studied the Sino-Brazilian beef SC and reported a lack of chain coordination from farm to consumer, arising from an undeveloped traceability mechanism, a limited flow of reliable information between the stages, and low trust between the stakeholders. Even though supply chain coordination can lead to better performance, either through financial performance, partnership performance, and/or sustained competitive advantage (Ralston et al., 2017), achieving collaboration throughout the SC is considered an intricate matter in the literature, because it is highly dependent on how the SC members perceive and interpret their roles and the roles of the other members in the SC (Skippari et al., 2017). In fact, Gaytán et al. (2017) mention that in Mexico the information does not flow with the speed, accuracy and certainty that all SC members need, making the decision-making risky and costly and compromising the efficiency of the exportation process. This supports the idea that the success of a business, the reduction of costs and, ultimately, the consumer's satisfaction depends on a well-managed, integrated and flexible logistics system, where information flows efficiently and is controlled in real time (Chávez et al., 2017). The beef sector seems to be very vulnerable to consumers' dissatisfaction. To counter this situation, the sector needs to seek integrated solutions to the inefficiencies of the beef SC, instead of seeking short term advantages (Watson, 1994). In sum, logistic solutions seem to have greater ability to combat FLW in beef SCs, as Liljestrand (2017) already discussed in a multiple-case study conducted in three food SCs of meat, fruit and vegetables, and ambient products.

3.7. Conclusion

FLW in the Brazilian beef SC has been overlooked in the literature so far. To implement appropriate mitigation strategies, first we need to identify the causes of FLW and assess their interrelatedness. In this paper, a literature review identified 20 main causes of FLW, from which 16 were considered relevant in the Brazilian beef SC by a set of experts. Next, the ISM methodology was applied to structure the selected causes into a hierarchy and divide them into six different levels of influence. Then, the sixteen causes were categorised into four different clusters, according to the dependence and driving powers determined by the MICMAC analysis. Five root causes of FLW were identified the: lack of transportation infrastructures, inadequate handling, poor operational performance, variety of products available in supermarkets and unhealthy animals and outbreaks of disease.

This research also reveals how the causes of FLW affect each other and provides valuable insights for researchers, practitioners and policy-makers to design and select appropriate policies and strategies to effectively mitigate the causes of FLW and ultimately prevent FLW within the Brazilian beef SC. The results reveal that the causes of FLW have essentially three different natures that can be related to logistics, to demand and to the product's characteristics. The further development of the Brazilian beef SC and the effective fight against FLW seems to depend on the country's ability to improve transportation infrastructures, to improve the transportation of live animals and their handling from farms to slaughterers, to adjust the variety of products in supermarkets to the needs of today's consumers and to improve sanitary control and inspections to prevent unhealthy animals and outbreaks of disease.

So, even though this paper contributes to the discussion on the reduction of FLW by analysing the causes from an SC perspective and proposes a three-phase methodology to identify the root causes of FLW that could be used as the starting point for setting FLW mitigation strategies, it also has some limitations. First, the results depend on the opinions of few experts and, second, the results may not be applicable or generalizable to other commodities or countries. However, these limitations are opportunities for future research.

Since the ISM and the MICMAC methodologies are based on the opinion of only a few experts, the model developed should be tested using a questionnaire survey and validated statistically by structural equation modelling (SEM). Post-hoc validation of the model using a large-scale survey would also be beneficial for generalising the results. Moreover, even though the results are most likely representative of other developing countries, particularly for other Latin-American countries with similar food supply chains and infrastructures like Brazil (for example, Argentina, Mexico, Colombia or Chile), the three-phase methodology should be replicated in other countries to assess how different SC dynamics impact on the relationships among the causes of FLW. This will help in the selection of the most appropriate mitigation strategies for different countries. The methodology should also be replicated for other commodities to help with the identification of the root causes of FLW and investigate what consequences they will have concerning the selection of the most suitable mitigation strategies. The methodology described in this paper should always be applied from an SC perspective to ensure the relevance of the results. Future investigations are also needed to understand which mitigation strategies are most appropriate to combat FLW, because there is a scarcity of information regarding how these strategies should be selected or implemented and it is still unclear which ones are the most effective to combat FLW.

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Chapter 4

Prioritising Food Loss and Waste Mitigation Strategies: A Hybrid Fuzzy SWARA – Fuzzy WASPAS approach

Abstract

Although reducing food loss and waste is a global concern, there is a scarcity of literature devoted to the selection of suitable mitigation strategies. Previous studies have been more focused on the disposal or valorisation options of food loss and waste, rather than on its reduction or prevention, and the effectiveness of mitigation strategies to reduce food loss and waste has hardly been evaluated. Therefore, this study develops and presents an evaluation framework to: (1) identify potential mitigation strategies based on the causes of food loss and waste, (2) select criteria to assess the prevention measures and (3) evaluate and rank mitigation strategies. Fuzzy Step-Wise Weight Assessment Ratio Analysis is employed to determine the relative weights of the evaluation criteria and Fuzzy Weighted Aggregated Sum Product Assessment is implemented to rank the mitigation strategies for food loss and waste. The evaluation framework is further tested in Portugal in the context of the Fruit and Vegetable Supply Chain. A sensitivity analysis was conducted to assess the robustness of the methodology proposed. Overall, sixteen mitigation strategies were selected and considered relevant to tackle the causes of food loss and waste in the Portuguese Fruit and Vegetable Supply Chain. Results show that the responsibility of reducing food loss and waste must be shared between all members of the supply chain. Mainly because the higher ranked mitigation strategies are the most transversal to the Fruit and Vegetable Supply Chain, which highlights the role of collaboration, coordination and information sharing between the stakeholders in the prevention and reduction of food loss and waste. This paper provides researchers, practitioners and policymakers with a comprehensible and structured approach to prioritise cost effective efforts with higher environmental and social gains.

Keywords: Food loss and waste; Fruit and vegetable supply chain; Mitigation strategies; Fuzzy step wise weight assessment ratio analysis; Fuzzy weighted aggregated sum product assessment; Portugal.

4.1. Introduction

About 1.3 billion tonnes (metric tons) of the global food produced for human consumption is lost or wasted each year (Gustavsson et al., 2011), corresponding to a total economic loss of 940 billion US$ (Fujii and Kondo, 2018), with fruit and vegetables representing 40 to 50% of this food loss and waste (FLW) (Gustavsson et al., 2011). FLW will only get worse, given that the rapidly growing world population will place an unprecedented pressure on the planet's natural resources (De Laurentiis et al., 2020) and threaten food security (FAO, 2013). One way to address this issue is by reducing FLW, which seems to be the key to achieve a sustainable development and a balance between economic development and environmental protection (FAO, 2013). To prompt the different stakeholders to take action against the generation of FLW, the United Nations established the objective of halving per capita global food waste at retail and consumer levels and reduce food losses along production and supply chains by 2030 in their Sustainable Development Goals (SDGs) (United Nations, 2015).

The Food Waste Hierarchy has guided the prioritization of FLW prevention and management measures mainly according to environmental criteria (Papargyropoulou et al., 2014). However, when considering economic criteria, for example, other tools are needed to prioritise and optimise the measures (Cristóbal et al., 2018). Therefore, it has become critical to develop methodologies that allow us to prioritise mitigation strategies for FLW (Muth et al., 2019).

Even though many strategies have already been reported in the literature (e.g., Wunderlich and Martinez, 2018; Spang et al., 2019), there is a scarcity of literature that develops evaluation methodologies to assess the performance of the mitigation strategies implemented (Schneider, 2013; Goossens et al., 2019; De Laurentiis et al., 2020). A review of existing evaluation methods, carried out by Goossens et al. (2019), has evidenced that very few studies reported the environmental, economic, and social impacts of the mitigation strategies and that their efficiency was also rarely assessed. Furthermore, most of the evaluation frameworks in the literature do not include an analysis of the priority among the strategies (Fujii and Kondo, 2018). Redlingshöfer et al. (2020) argues that FLW prevention is under-represented in the literature and concluded that this neglect is a consequence of the fact that the Food Waste Hierarchy is mainly used by FLW managers, whose business models, goals and competences are focused on the treatment of FLW and not on its prevention. In sum, the study of the mitigation strategies for FLW is still at an early stage of development and appropriate methods to assess their effectiveness need to be developed to enable the identification of the best alternatives and the prioritisation of the most promising ones (De Laurentiis et al., 2020).

This paper addresses these shortcomings by presenting a research framework to rank and prioritise the mitigation strategies best suited to tackle the causes of FLW and reduce FLW along

FSCs, based on a set of criteria that may be used to evaluate measures to prevent FLW. The research question guiding this paper is:

(RQ) What are the potential mitigation strategies to tackle the causes of FLW and reduce FLW along FSCs?

To answer this research question a research framework was developed to: (1) identify potential mitigation strategies to tackle known causes of FLW; (2) define a set of feasible criteria to evaluate these strategies; (3) determine relative weights for the evaluation criteria; and (4) evaluate and rank the mitigation strategies for FLW according to their performance regarding each evaluation criterion.

The research framework proposed is based on multi-criteria decision making (MCDM) methods to prioritise the mitigation strategies for FLW. The fuzzy set theory is employed to accommodate complex situations and handle imprecise information (Agarwal et al., 2020). The fuzzy step-wise weight assessment ratio analysis (SWARA) is used to determine the weight of the evaluation criteria and the fuzzy weighted aggregated sum product assessment (WASPAS) is used to evaluate and rank the mitigation strategies for FLW. Fuzzy SWARA is easy to understand, requires less computation time than other MCDM methods and analyses experts' opinions to estimate the relative importance ratio of each criterion without using any scaling (Agarwal et al., 2020). Fuzzy WASPAS is based on the weighted product model (WPM) and weighted sum model (WSM) and prioritises alternatives based on the combined optimality criteria obtained from WPM and WSM (Agarwal et al., 2020). The methodology proposed provides some new insights that academics, practitioners, and stakeholders of FSCs could consider when selecting and implementing mitigation strategies for FLW.

The framework is applied in the context of the Portuguese fruit and vegetable supply chain (FVSC). Magalhães et al. (2021) modelled the interrelationships of the causes of FLW in the Portuguese FVSC and identified 14 main causes of FLW in the process, which guided the selection of potential mitigation strategies to be ranked by the research framework developed. The authors further argued that future investigations concerning the selection, evaluation and prioritisation of the mitigation strategies were needed and the research framework proposed in this paper is one of the earlier attempts to close this knowledge gap. The main findings of this paper highlight the role of information management in the reduction of FLW along the Portuguese FVSC and the framework proposed provides researchers, practitioners, and policymakers with a comprehensible and structured approach to prioritise the mitigation strategies for FLW in any context and supply chain.

The remainder of this paper is organized as follows: section 4.2 provides an overview of the literature on the mitigation strategies for FLW and the methods used to evaluate or prioritise them; in section 4.3, a research framework to identify and prioritise the mitigation strategies for

FLW is proposed; the research methodologies employed in this research are presented in section 4.4; the framework is applied in the context of the Portuguese FVSC in section 4.5, followed by a sensitivity analysis to assess the framework's robustness. Section 4.6 presents the results, section 4.7 discusses these in the light of the existing literature and the final conclusions are presented in section 4.8.

4.2. Literature Review on the Mitigation Strategies for FLW

Research on FLW has attracted extensive attention during the past decade (Chen et al., 2017). Investigations concerning FLW reduction often attempt to assess the environmental and/or economic gains that can be achieved by the reduction of FLW, through the means of scenario comparisons (e.g., Salemdeeb et al., 2017; de Gorter et al., 2020). However, the identification, evaluation and prioritisation of the solutions to prevent, reduce or manage FLW along FSCs also deserve attention. These contributions are summarised in Table 4.1. The table shows the methods employed in the literature to study the solutions to manage FLW along FSCs. It also assesses whether the contributions investigate mitigation strategies to reduce FLW along FSCs or strategies to manage FLW, such as re-use, recovery, recycling or disposal strategies. The works that investigated the mitigation strategies to reduce FLW along FSCs are identified within the table with an "MT" and the works that focused on management strategies instead are identified with an "M". The table further assesses whether the strategies are evaluated with environmental (EN), economic (EC) and/or social (S) criteria, and whether the priority between solutions is established. If the works summarised in the table address these criteria or refer to a priority between solutions they are marked with a "Y" (meaning Yes); alternatively, they are marked with an "N" (meaning No).

Table 4.1 – Summary of contributions focused on the solutions to FLW

Source	Method	Strategies	Evaluation Criteria			Priority Check
			EN	EC	S	
Hamilton et al. (2015)	Multilayer systems approach	MT/M	Y	N	N	N
Eriksson et al. (2016)	CBA	MT	Y	Y	N	N
Banasik et al. (2017)	MOMILP	MT/M	Y	Y	N	N
Creus et al. (2018)	LCA	MT	Y	N	N	N
Cristóbal et al. (2018)	LCA and ILP	MT/M	Y	Y	N	Y
Bais-Moleman et al. (2019)	LCA	MT/M	Y	N	N	N
Diaz-Ruiz et al. (2019)	Delphi	MT/M	N	N	N	Y
Goossens et al. (2019)	Review	MT/M	N	N	N	N
Muth et al. (2019)	Review	MT/M	Y	Y	N	N
Spang et al. (2019)	Review	MT/M	N	N	N	N
Stone et al. (2019)	CBA, LCA and WSM	M	Y	Y	Y	Y
De Laurentiis et al. (2020)	LCA	MT	Y	Y	Y	N
Dora et al. (2020)	SLR	M	N	N	N	N
Kleineidam (2020)	SLR and interviews	MT	N	N	N	N
Rodrigues et al. (2020)	Case study	MT	Y	Y	Y	N
Ciccullo et al. (2021)	Case study	MT	N	N	N	N

Note: MOMILP – Multi-Objective Mixed Integer Linear Programming; LCA – Life-Cycle Assessment; ILP – Integer Linear Programming; DEMATEL – Decision-Making Trial and Evaluation Laboratory; CBA – Cost-Benefit Analysis; WSM – Weighted Sum Model; SLR – Systematic Literature Review; DPSIR - Driver-Pressure-State-Impact-Response; MT – Mitigation Strategies (reduction of FLW); M – Management strategies (such as re-use, recovery, recycling or disposal of FLW); EN – Environmental; EC – Economic; S – Social; Y – Yes; N – No.

The contributions to the identification, evaluation and prioritisation of the solutions for FLW are very diverse, because when researchers call for the identification of solutions to tackle FLW along FSCs, they may be related to the prevention, re-use, recycling, recovery or disposal of FLW, which are the different options according to the Food Waste Hierarchy (Papargyropoulou et al., 2014). Indeed, the majority of the contributions investigate FLW management strategies, like re-use, recovery, recycling or disposal strategies, instead of FLW mitigation strategies focusing on its reduction or prevention along FSCs. For instance, Dora et al. (2020) developed a conceptual framework, based on the lens of the circular economy, to establish measures to re-use, reduce, recycle and recover FLW in order to use minimal inputs and close nutrient loops within a potato supply chain. Hamilton et al. (2015) used a multilayer system approach to quantify the environmental impacts of recycling and prevention on national biomass, energy, and phosphorus cycles and concluded that prevention strategies should be prioritised rather than the recycling ones. Later, Banasik et al. (2017) developed a MOMILP model to assess alternative bread production options (par-baked bread - prevention, fermented breadcrumb bread - recycling, and freshly baked bread - disposal) and concluded that prevention was the most beneficial option, according to its environmental and economic performance. The LCA methodology has also been employed in the literature to evaluate the environmental gains of switching from less preferable FLW management options (like recycling or recovery) to more favourable ones (like prevention or reuse). Bais-Moleman et al. (2019), on the other hand, compared the performance of different measures to tackle FLW (changing human diet, using food waste in livestock diets, shifting from monoculture cropping to crop rotation, and incorporating crop residues into the soil) and concluded that their implementation could increase land use savings from 0.06 to 3.32 m2/person/day and GHG emission savings from 71 to 1,872g CO2-eq/person/day. More recently, De Laurentiis et al. (2020) developed a conceptual framework based on LCA to assess the environmental, economic and social performance of FLW prevention and redistribution measures. Even though this seems to be a suitable and complete framework to evaluate and prioritise FLW solutions, its implementation needs a lot of data that might not be known or available beforehand.

The works of Eriksson et al. (2016), Kleineidam (2020) and Ciccullo et al. (2021) investigate the reduction of FLW at the source. Eriksson et al. (2016) showed the potential that reducing the storage temperature had to prolong the product’s shelf life thereby decreasing FLW. Through a cost-benefit analysis, the author concluded that decreasing storage temperature in meat products from Swedish supermarkets could increase the net savings in terms of money and greenhouse gas emissions. Kleineidam (2020) used a systematic literature review and interviews with experts to identify fields of action underlying the design of logistics-related measures to reduce FLW along FSCs. Ciccullo et al. (2021) interviewed technology providers and experts from the agri-food supply chain to study the role of the technologies available (related to forecasting, monitoring, shelf-life extension, product quality and value upgrading) in preventing FLW.

The contributions described above can evaluate different measures from environmental, economic and/or social perspectives, but they do not allow their direct comparison or prioritisation, since they do not estimate an aggregated score to be compared. To overcome this limitation, Diaz-Ruiz et al. (2019) used a multi-actor approach to prioritise 48 measures to prevent FLW. The author used the Delphi method to evaluate the consensus or dissensus of the experts interviewed regarding the effectiveness of each prevention measure. Cristóbal et al. (2018) applied a methodology using LCA and ILP to prioritise different FLW prevention, reuse and recycling-recovery measures. The “quick-wins” that resulted from the application of this methodology often highlighted reuse or recycling-recovery measures before preventive ones, since they were more cost-effective than the latter. Other methods in the literature show potential to prioritise alternatives, particularly the MCDM techniques, which enable practitioners and decision-makers to identify the most significant solutions (Malek and Desai, 2019). Stone et al. (2019) used the WSM methodology to rank two different FLW valorisation options, according to their environmental, economic and social performance. More recently, Prajapati et al. (2019) used a SWARA and WASPAS approach to estimate the relative importance of 34 barriers to reverse logistics implementation and to prioritise 21 proposed solutions. Agarwal et al. (2020) used a fuzzy SWARA and fuzzy WASPAS approach to evaluate the relative weight of 29 barriers hindering the implementation of improved humanitarian supply chains and prioritised 20 solutions to overcome those barriers.

The MCDM approaches are very successful in estimating an overall score that enables a direct comparison of alternatives, but the prioritisation of the mitigation strategies for FLW should be based on the strategies' environmental, economic and social performance (Goossens et al., 2019). Goossens et al. (2019) provides a complete review of the different evaluation criteria to assess FLW prevention measures and recommends that the solutions to FLW should be assessed based on: their effectiveness, i.e. their potential to decrease FLW, on the solutions' sustainability; their performance regarding environmental, economic and social aspects, and their efficiency. This balances the costs of a solution against its economic benefits, its waste diversion potential (the amount of FLW that was reduced or prevented), or the resulting ecological savings, such as the reduction of emissions. The authors further stress that very few studies in the literature report the effectiveness of the mitigation strategies, evaluate their environmental, economic, and social impacts or assess their efficiency, which hinders the comparison of different mitigation strategies, the dissemination of best practices and the prioritisation of potential FLW solutions.

The environmental impact of a mitigation strategy for FLW balances the related impacts avoided, associated with the food that is no longer wasted and aspects concerning disposal and the environmental impact that may be created or saved by the implementation of the mitigation strategy itself (Goossens et al., 2019). These are typically estimated along the entire FSC with a cost-benefit analysis, multi-criteria decision analysis, LCA or environmentally extended input-output (EEIO) models (Goossens et al., 2019; Spang et al., 2019; Muth et al., 2019). Some of the metrics used to convey the environmental impacts include CO2 eq. emissions, the blue water footprint, the energy consumed and the solid waste produced (Banasik et al., 2017; Rodrigues et al., 2020).

The economic impact of a mitigation strategy for FLW comprises the embodied economic costs avoided, the disposal costs avoided and the implementation costs or savings (Goossens et al., 2019). These impacts can be estimated by net benefits, cost-benefit analysis or cost-effectiveness methods (Goossens et al., 2019; Muth et al., 2019). To account for the volume of FLW reduction or the respective ecological savings in the benefits obtained through the implementation of a food waste measure, these indicators should be expressed in a monetary value, since these methods only deal with monetary data (Goossens et al., 2019). The typical metrics used to convey the economic impacts comprise the opportunity cost, the value of lost sales, the ratio of FLW in each stage of the supply chain, the financial cost, the economic value, or the financial benefit of the mitigation strategy (Cristóbal et al., 2018; Rodrigues et al., 2020).

The social effects of a mitigation strategy for FLW are more difficult to assess, since there are usually no models or methods to quantify these effects. The new jobs that may be created or eliminated due to the implementation of a mitigation strategy (Goossens et al., 2019) or the discount sales to employees (Rodrigues et al., 2020) can be used as metrics to assess the social dimension of a mitigation strategy.

Recently, the European Commission Joint Research Centre (JRC) developed an evaluation framework to assess the performance of FLW prevention actions according to six criteria: quality of the action design, effectiveness, efficiency, sustainability of the action over time, intersectorial cooperation and transferability and scalability (De Laurentiis et al., 2020). These criteria encompass different indicators to evaluate the performance of prevention actions, enabling the identification of best practices and the prioritisation of the most promising ones.

In conclusion, most of the works discussed here focused on the comparison of the disposal, recycling, recovery or re-use strategies versus the mitigation strategies for FLW, showing that the evaluation of the mitigation strategies to reduce FLW is still at an early stage of development (De Laurentiis et al., 2020). The methods employed also showed some limitations in using the environmental, economic and social performances to rank or establish priorities between the different solutions. Therefore, to overcome these limitations, the present study develops a framework based on MCDM techniques to prioritise the mitigation strategies to reduce FLW, according to their environmental, economic and social performance.

4.3. Framework Proposed

To help decision-makers identify and prioritise the mitigation strategies best suited to tackle the relevant causes of FLW and reduce FLW along FSCs, and based on a set of criteria to evaluate FLW prevention measures, we propose the three-phase framework depicted in Figure 4.1.

Phase I: Identifying potential mitigation strategies and defining the evaluation criteria

The first phase of the proposed research framework starts with a review of the literature and a focus group discussion (FGD) that enables the identification of: (1) a set of mitigation strategies to reduce FLW, and (2) a set of feasible evaluation criteria to analyse each alternative's performance.

A literature review should be performed to gather knowledge that will be useful to guide the FGDs and to compile a list of potential mitigation strategies that can tackle the causes of FLW. Magalhães et al. (2021) identified the main causes of FLW in the FVSC (see Table 4.2), which were used in this research to initiate the implementation of the research framework in the Portuguese FVSC context and guide the literature review.

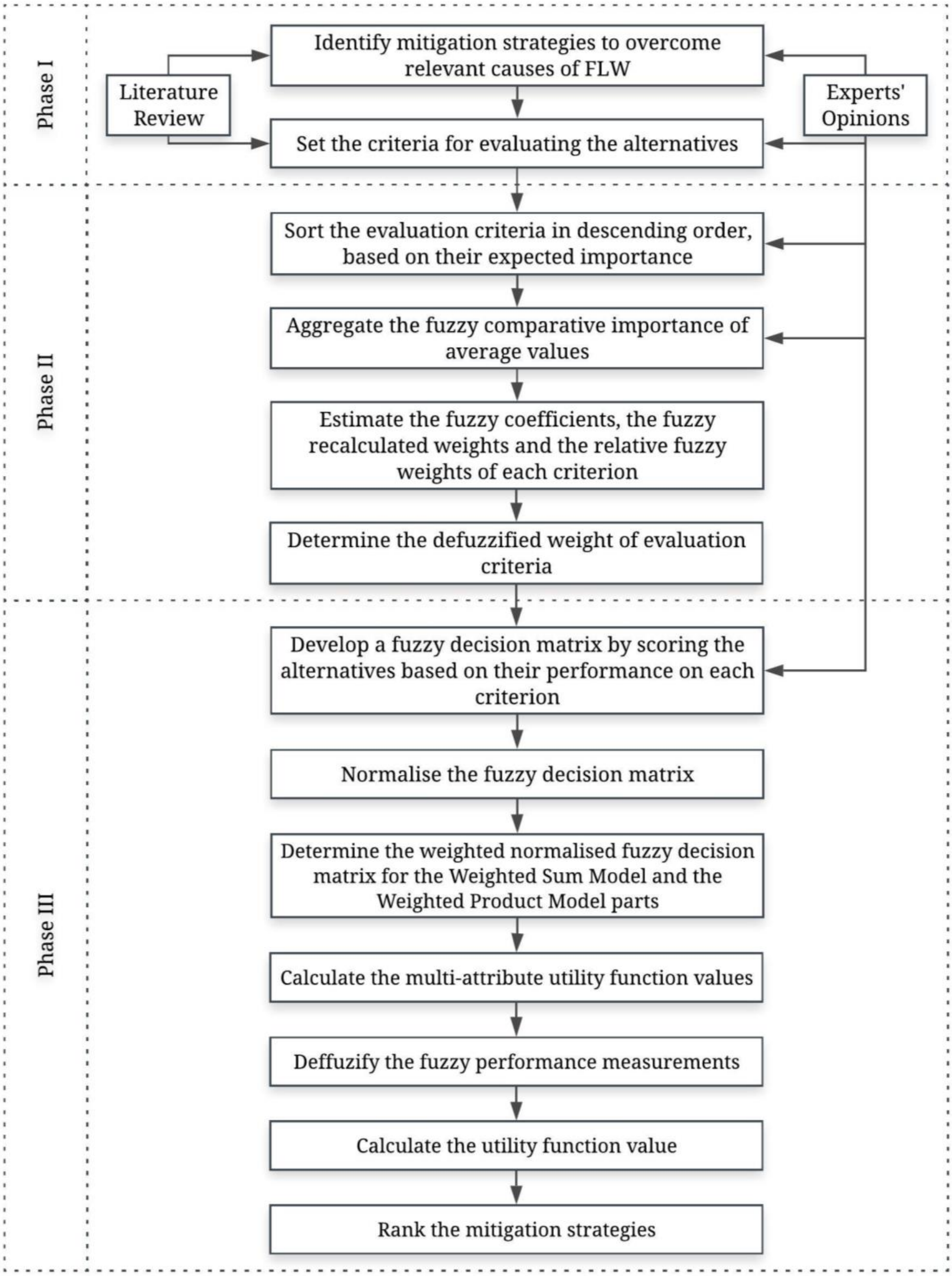

Figure 4.1 – Evaluation framework proposed to identify and rank mitigation strategies for FLW

Table 4.2 – Causes of FLW identified in the work of Magalhães et al. (2021)

Nr.	Cause of FLW	Nr.	Cause of FLW
C01	Inadequate demand forecasting	**C08**	Short shelf-life or expired products
C02	Overproduction and excessive stock	**C09**	Climate change and weather variability
C03	Poor handling and operational performance	**C10**	Lack of storage facilities
C04	Storage at wrong temperature	**C11**	Pricing strategies and promotions management
C05	Inadequate or defective packaging	**C12**	Lack of coordination and information sharing
C06	Non-conformance to retail specifications	**C13**	Inadequate transportation systems
C07	Sensorial or microbial deterioration	**C14**	Inefficient in-store management

To further enable the implementation of the research framework, different actors of the FVSC were invited to take part in this study. The FGD research technique is an exploratory approach commonly used to enhance the previously known information about a subject or to investigate it from a different point of view through the interaction of a group of experts (Nassar-McMillan and Borders, 2002). To create new insights concerning a certain subject, the moderator must assume a leadership role during the conversation and stimulate discussion among the participants. The selected participants are gathered to discuss and share experiences, opinions, and perceptions based on their knowledge (Kristensen et al., 2021; Krueger and Casey, 2015) and should be able to provide high quality information regarding the subject under study. It is therefore critical to base the selection of the participants on very specific criteria to ensure that they have the best profile for the discussions (Greenbaum, 1998). In this study, seven experts were selected, following the guidelines presented by Greenbaum (1998), to comprise a focus group and discuss the issue of the reduction of FLW in the FVSC. The sampling method used to select the experts was the purposive sampling method, also known as judgment sampling method, since this method is typically used in qualitative research to identify people with knowledge of the topic, so that experts who are proficient and well-informed with the topic under study are selected (Harrel and Bradley, 2009; Etikan et al., 2016). The experts were chosen based on their considerable experience in importing, producing, distributing, selling and exporting fruits and vegetables, to enable a holistic understanding of the mitigation strategies for FLW along the FVSC. Their profiles are presented in Table 4.3.

The focus group met during two different sessions with average durations of 120 minutes each. The discussions were moderated by at least two of the authors, to ensure that there was always one author present with knowledge about the topics of supply chain management and FLW, and their role was to guide the discussions from general to specific topics, help the group to reach extensive consensuses, endorsing sincerity and reducing bias.

The first discussion with the focus group in this phase was useful to finalise the list of mitigation strategies to be studied and to select the evaluation criteria that should be used to assess the performance of the strategies concerning the reduction of FLW (see section 4.6.1 for more details).

Table 4.3 – Profile of the experts

Nr.	Type of activity	Designation
1	F&V Producer	Senior Operations Manager
2	F&V Producer	Operations Manager
3	Logistics Operator	Logistics and FSC Manager
4	Retailer	Procurement Manager
5	Retailer	Chief-executive of the sales department
6	Academics	Professor
7	Academics	Professor

Phase II: Determining the relative weights of the evaluation criteria

In the second phase, the relative weights of the evaluation criteria are determined based on the experts' decisions, using the fuzzy SWARA method.

During the second session of the FGD, the experts are asked to organise the evaluation criteria according to their importance (i.e., from the most to the least important) and to judge their relative importance. The decisions have to be made as a group and the moderators of the discussion are responsible for ensuring that a consensus is reached. Subsequently, the individual weight of each criterion is estimated with fuzzy SWARA.

Phase III: Assessing and ranking suitable mitigation strategies

In the third phase of the research framework proposed, the fuzzy WASPAS approach is applied to rank the mitigation strategies selected in Phase I by using the evaluation criteria' weights obtained in Phase II.

In the second FGD session, the experts are also asked to assess the mitigation strategies' performance for each evaluation criterion, using a fuzzy evaluation scale. After reaching a consensus, the assessments are recorded in a decision-making matrix and the mitigation strategies are ranked using the fuzzy WASPAS approach.

4.4. Methods

A hybrid SWARA and WASPAS methodology was first introduced to rank different locations of a shopping centre (Zolfani et al., 2013). More recently, it has been used successfully to prioritise the solutions of reverse logistics implementation (Prajapati et al., 2019) and, an extension of the methodology to a hybrid fuzzy SWARA – fuzzy WASPAS approach, has been used to rank the solutions to overcome the barriers to humanitarian supply chain management (Agarwal et al., 2020). This approach is easy to implement and the ranking of alternatives has great reliability in solving decision-making problems (Agarwal et al., 2020). This research incorporates the FGD research technique with the hybrid fuzzy SWARA – fuzzy WASPAS approach, wherein the fuzzy SWARA method is used to determine the relative weights of the criteria to evaluate the preventive measures adopted for FLW and the fuzzy WASPAS method is used to prioritise the list of mitigation strategies for FLW.

For the implementation of the fuzzy SWARA and fuzzy WASPAS methodology, four basic arithmetic operations on triangular fuzzy numbers are need. If $A_1 = (a_1, b_1, c_1)$ and $B_1 = (a_2, b_2, c_2)$, then:

Fuzzy addition:

$$A_1 + B_1 = (a_1 + a_2,\ b_1 + b_2,\ c_1 + c_2) \tag{1}$$

Fuzzy subtraction:

$$A_1 - B_1 = (a_1 - a_2,\ b_1 - b_2,\ c_1 - c_2) \tag{2}$$

Fuzzy multiplication:

$$A_1 \times B_1 = (a_1 a_2,\ b_1 b_2,\ c_1 c_2) \tag{3}$$

Fuzzy division:

$$A_1 \div B_1 = \left(\frac{a_1}{c_2}, \frac{b_1}{b_2}, \frac{c_1}{a_2}\right) \tag{4}$$

4.4.1 Fuzzy Step-wise Weight Assessment Ratio Analysis (SWARA) Method

The SWARA method was introduced by Keršuliene et al. (2010) to estimate the relative importance ratio of criteria, based on the opinions and judgements of experts. It has the ability to estimate the experts' preferences regarding the significance of the attributes in the process of weight determination (Perçin, 2019). The advantage of the SWARA method is that it requires fewer comparisons (n-1) than, for instance, AHP or ANP that requires n(n-1). Also, there is no need to check for inconsistencies in the experts' judgement since the method ranks the criteria in descending order (Agarwal, Kant and Shankar, 2020). Although the SWARA and the Best Worst Method (BWM) implementations are very similar, SWARA can be more accurate and effective (Zolfani and Chatterjee, 2019). To accommodate complex or unusual situations and handle imprecise and vague information, SWARA can be upgraded to use a fuzzy approach, with the benefit of assigning a fuzzy number, instead of a precise one, to the relative importance of the criteria (Agarwal, Kant and Shankar, 2020).

According to Mavi et al. (2017), Zarbakhshnia et al. (2018), Perçin (2019) and Agarwal et al. (2020) the fuzzy SWARA method can be summarised in the following steps:

(1) Organise the evaluation criteria from the most to the least expected significance, based on the experts' opinions.

(2) According to Table 4.4 and beginning with the second most significant criterion, the experts should judge the relative importance of criterion j compared to the previous (j-1) criterion

and the process should be repeated until the least significant criterion. This ratio is called the Comparative Importance of the Average Value, $\widehat{S_j}$ (Keršuliene, Zavadskas and Turskis, 2010).

Table 4.4 – Linguistic comparison scale and corresponding triangular fuzzy numbers (Agarwal, Kant and Shankar, 2020)

Linguistic comparison scale	Triangular fuzzy number
Extremely unimportant	(0.0, 0.0, 0.1)
Not very important	(0.0, 0.1, 0.3)
Not important	(0.1, 0.3, 0.5)
Fair	(0.3, 0.5, 0.7)
Important	(0.5, 0.7, 0.9)
Very important	(0.7, 0.9, 1.0)
Extremely important	(0.9, 1.0, 1.0)

(3) Estimate the coefficient value, $\hat{k}_j$, the fuzzy recalculated weights, $\hat{q}_j$, and the relative fuzzy weights, $\widehat{w}_j$ for each criterion:

$$\hat{k}_j = \begin{cases} 1 & j = 1 \\ \hat{S}_j + 1 & j > 1 \end{cases} \tag{5}$$

$$\hat{q}_j = \begin{cases} 1 & j = 1 \\ \dfrac{\hat{q}_{j-1}}{\hat{k}_j} & j > 1 \end{cases} \tag{6}$$

$$\widehat{w}_j = \frac{\hat{q}_j}{\sum_{k=1}^{n} \hat{q}_k} \tag{7}$$

where $\widehat{w}_j$ = (a, b, c) is the fuzzy relative importance weight of the j^{th} criterion and n is the number of criteria.

(4) Estimate the defuzzified relative weights of evaluation criteria, w_j, by using the following centroid method equation:

$$w_j = \frac{1}{3}\widehat{w}_j = \frac{1}{3}\left(\widehat{w}_{j\alpha} + \widehat{w}_{j\beta} + \widehat{w}_{j\gamma}\right) \tag{8}$$

4.4.2 Fuzzy Weighted Aggregated Sum Product Assessment (WASPAS) Method

The WASPAS method was developed by Zavadskas et al. (2012) and is considered one of the most robust MCDM methods (Agarwal, Kant and Shankar, 2020). WASPAS aggregates the Weighted Sum Model (WSM) and Weighted Product Model (WPM) methods. The WSM approach estimates the total score of the alternative as a weighted sum of the criteria, while the WPM approach avoids alternatives that have poor attributes or criterion values (Turskis *et al.*, 2019). The WASPAS method evaluates alternatives in terms of several decision criteria using WSM, then evaluates alternatives in terms of multiplicative exponential criteria using WPM and, finally, evaluates the weighted aggregation of the additive and multiplicative method, representing a more realistic situation (Agarwal, Kant and Shankar, 2020). WASPAS demonstrates better yields than WSM and WPM, operating more correctly than other MCDM methods and enabling the evaluation and ranking of alternatives with a higher reliability (Agarwal, Kant and Shankar, 2020).

The benefits of extending WASPAS to use the fuzzy sets approach are the same as the ones explained previously for the SWARA method. In sum, the fuzzy approach can deal better with imprecise and vague information, helping to deal with complex problems. According to Turskis et al. (2015), Turskis et al. (2019) and Agarwal et al. (2020) the fuzzy WASPAS method can be resumed in the following steps:

(1) Prepare the fuzzy decision making matrix (DMM), using the scale from Table 4.4:

$$\tilde{X} = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1j} & \cdots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \tilde{x}_{i1} & \cdots & \tilde{x}_{ij} & \cdots & \tilde{x}_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \cdots & \tilde{x}_{mj} & \cdots & \tilde{x}_{mn} \end{bmatrix}; \ i = \overline{1,m}; j = \overline{1,n} \quad (9)$$

where n is the number of evaluation criteria, m is the number of alternatives and $\tilde{x}_{ij}$ is the fuzzy evaluation of the ith alternative against the jth decision criterion. The tilde symbol "~" indicates a fuzzy set.

(2) Normalise the fuzzy DMM according to the optimum value of the evaluation criteria. If the maximum value is preferred:

$$\tilde{\bar{X}}_{ij} = \frac{\tilde{x}_{ij}}{max\tilde{x}_{ij}}; i = \overline{1,m}; \ j = \overline{1,n} \quad (10)$$

If the minimum value is preferred:

$$\tilde{\bar{X}}_{ij} = \frac{min\tilde{x}_{ij}}{\tilde{x}_{ij}}; i = \overline{1,m}; \ j = \overline{1,n} \quad (11)$$

(3) Determine the weighted normalised fuzzy DMM for the WSM part:

$$\tilde{\hat{X}}_q = \begin{bmatrix} \tilde{\hat{x}}_{11} & \cdots & \tilde{\hat{x}}_{1j} & \cdots & \tilde{\hat{x}}_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \tilde{\hat{x}}_{i1} & \cdots & \tilde{\hat{x}}_{ij} & \cdots & \tilde{\hat{x}}_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \tilde{\hat{x}}_{m1} & \cdots & \tilde{\hat{x}}_{mj} & \cdots & \tilde{\hat{x}}_{mn} \end{bmatrix}; \ \tilde{\hat{x}}_{ij} = \tilde{\bar{x}}_{ij}\tilde{w}_j; i = \overline{1,m}; j = \overline{1,n} \quad (12)$$

(4) Determine the weighted normalized fuzzy DMM for the WPM part:

$$\tilde{\hat{X}}_p = \begin{bmatrix} \tilde{\bar{\bar{x}}}_{11} & \cdots & \tilde{\bar{\bar{x}}}_{1j} & \cdots & \tilde{\bar{\bar{x}}}_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \tilde{\bar{\bar{x}}}_{i1} & \cdots & \tilde{\bar{\bar{x}}}_{ij} & \cdots & \tilde{\bar{\bar{x}}}_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \tilde{\bar{\bar{x}}}_{m1} & \cdots & \tilde{\bar{\bar{x}}}_{mj} & \cdots & \tilde{\bar{\bar{x}}}_{mn} \end{bmatrix}; \ \tilde{\bar{\bar{x}}}_{ij} = \tilde{\bar{x}}_{ij}^{\tilde{w}_j}; i = \overline{1,m}; j = \overline{1,n} \quad (13)$$

(5) Calculate the fuzzy multi-attribute utility function values for the WSM and WPM parts, for each alternative:

$$\tilde{Q}_i = \sum_{j=1}^{n} \tilde{\hat{x}}_{ij}\,;\; i = \overline{1,m} \tag{14}$$

$$\tilde{P}_i = \prod_{j=1}^{n} \tilde{\bar{\bar{x}}}_{ij}\,;\; i = \overline{1,m} \tag{15}$$

(6) Defuzzify the fuzzy performance measurements using the centre-of-area method, which is the most practical and easiest way:

$$Q_i = \frac{1}{3}(Q_{i\alpha} + Q_{i\beta} + Q_{i\gamma}) \tag{16}$$

$$P_i = \frac{1}{3}(P_{i\alpha} + P_{i\beta} + P_{i\gamma}) \tag{17}$$

(7) Estimate the utility function value of the fuzzy WASPAS method:

$$K_i = \lambda \sum_{j=1}^{n} Q_i + (1-\lambda) \sum_{j=1}^{n} P_i\,;\, \lambda = \overline{0{,}1}; 0 \leq K_i \leq 0 \tag{18}$$

Where λ is a combination parameter estimated by:

$$\lambda = \frac{\sum_{i=1}^{m} P_i}{\sum_{i=1}^{m} Q_i + \sum_{i=1}^{m} P_i} \tag{19}$$

When the value of λ is 0, the WASPAS method is transformed into the WPM method, and when λ is 1, it becomes the WSM method.

(8) Rank the alternatives from the highest to the lowest K_i value.

4.5. Application of the Proposed Research Framework

The proposed research framework was tested to identify, evaluate and rank a set of mitigation strategies with the potential to tackle the causes of FLW in the FVSC.

4.6.1 Phase I – Identifying potential mitigation strategies and defining the evaluation criteria

To ascertain the final list of mitigation strategies to study, an analysis of the literature was performed, from which 20 different mitigation strategies, presented in Table B1 from Appendix B, were initially identified and listed. Then, during the first focus group discussion, the panel of experts was invited to discuss their experiences with FLW and to discuss the actions they thought best to mitigate FLW. More specifically, they were asked to evaluate which mitigation strategies collected from the literature review were relevant to tackle FLW in the FVSC and to list any other mitigation strategy not referred to in the literature, if necessary. The experts agreed on the relevance of 16 out of the 20 mitigation strategies listed. The mitigation strategies selected are detailed in Table 4.5. The literature review and the FGD also made it possible to assess the causes of FLW that were tackled by each mitigation strategy and during which stages of the FVSC the mitigation strategies should be implemented, highlighting the members of the FVSC responsible for implementing the mitigation strategies for FLW (Table 4.6).

Table 4.5 – Mitigation strategies to tackle the causes of FLW in FVSCs

Nr.	Mitigation Strategy	Reference
Information-related Mitigation Strategies:		
S01	Develop and use intelligent packaging to monitor products' safety and quality	Rossaint and Kreyenschmidt (2015); Verghese et al. (2015)
S02	Ensure communication among FSC stages	Kaipia et al. (2013)
S03	Implement integrated IT systems throughout FSCs	Mena et al. (2011); Liljestrand (2017)
S04	Implement automated demand forecasting systems	Mena et al. (2011); Liljestrand (2017)
S05	Share and maintain information regarding the remaining shelf-life	Kaipia et al. (2013); Macheka et al. (2013); Munesue et al. (2015); Gadde and Amani (2016); Chen and Chen (2018)
S06	Improve visibility along FSCs through traceability systems	Mena et al. (2011); Verghese et al. (2015)
S07	Find new markets for overproduction or products sorted out due to industry's quality standards	Calvo-Porral et al. (2017); Plazzotta et al. (2017); Chen and Chen (2018)
Quality-related Mitigation Strategies:		
S08	Training staff on handling practices	Macheka et al. (2013); Munesue et al. (2015); Emana et al. (2017); Chen and Chen (2018)
S09	Ensure adherence to standard procedures	Macheka et al. (2013)
S10	Adjust packaging size	Richter and Bokelmann (2016); Chen and Chen (2018)
S11	Correct date marking to avoid confusion	Wikström et al. (2014); Verghese et al. (2015)
S12	Invest in more and regularly maintain storage facilities	Munesue et al. (2015); Tesfay and Teferi (2017)
Technology-related Mitigation Strategies :		
S13	Develop new packaging and preservation techniques to enhance product's shelf-life	Mena et al. (2011); Mercier et al. (2017)
S14	Improve cooling methods	Emana et al. (2017)
Transport and Infrastructures-related Mitigation Strategies:		
S15	Improve transport infrastructures	Gardas et al. (2017); Nourbakhsh et al. (2016)
S16	Improve the means of transportation	Nourbakhsh et al. (2016); Gardas et al. (2017); Lipińska et al. (2019)

Table 4.6 shows that the mitigation strategies that are transversal to the FVSC (meaning that they should be implemented in all stages of the FVSC) are more related to Information (as seen in Table 4.5) with the exception of the strategy to Train staff on handling practices (S08), which is related to Quality-related strategies. Overall, the table clearly shows that the efforts to reduce FLW along the FVSC must be made by all members of the FVSC.

Table 4.6 – Causes of FLW tackled by each mitigation strategy and FVSC stages where they should be implemented in

	Cause														FVSC Stage				
	C01	**C02**	**C03**	**C04**	**C05**	**C06**	**C07**	**C08**	**C09**	**C10**	**C11**	**C12**	**C13**	**C14**	**A**	**H**	**P**	**D**	**R**
S01				✓	✓	✓	✓	✓				✓		✓			✓	✓	✓
S02	✓	✓		✓							✓	✓			✓	✓	✓	✓	✓
S03	✓	✓		✓				✓			✓	✓			✓	✓	✓	✓	✓
S04	✓	✓									✓	✓			✓	✓	✓	✓	✓
S05	✓	✓				✓	✓	✓			✓	✓		✓		✓	✓	✓	✓
S06				✓		✓	✓	✓			✓	✓		✓	✓	✓	✓	✓	✓
S07		✓				✓	✓	✓	✓				✓		✓			✓	✓
S08			✓			✓									✓	✓	✓	✓	✓
S09			✓			✓									✓	✓			
S10		✓			✓						✓			✓			✓		✓
S11					✓			✓									✓		✓
S12				✓		✓	✓	✓		✓				✓		✓	✓	✓	✓
S13					✓	✓	✓	✓						✓			✓	✓	✓
S14				✓		✓	✓	✓		✓				✓		✓	✓	✓	✓
S15					✓	✓	✓	✓					✓				✓	✓	✓
S16				✓	✓	✓	✓	✓					✓				✓	✓	✓

Note: A- Agricultural production; H – Post-harvest handling and storage; P – Processing and packaging; D – Distribution; R – Retail and Wholesale.

During the first FGD, the experts also discussed the most suitable set of evaluation criteria to evaluate the environmental, economic and social performance of the mitigation strategies under study. After analysing the different indicators to assess the performance of mitigation strategies on the environmental, economic and social dimensions summarised in the literature review, the experts agreed that the set of criteria proposed by the European Commission JRC (De Laurentiis et al., 2020) were the most appropriate to assess the mitigation strategies under study. The evaluation criteria will now be outlined. **Quality of the Action Design (EC1):** relates to the definition of the aim and objective of the mitigation strategy, the strategy and implementation plan to achieve it, the key performance indicators (KPIs) and the monitoring system to track progress regarding the targets set. **Effectiveness (EC2):** refers to the degree to which a mitigation strategy was successful in reaching the desired outcomes. It should be estimated based on how much FLW was reduced compared to a baseline scenario, but in some cases this is not feasible to estimate. In those cases, other outcomes may be measured instead (e.g. the number of people reporting a change in behaviour as a result of a campaign). **Efficiency (EC3):** refers to the ability to reach a desired outcome with the least effort, accounting for all the resources used to implement the mitigation strategy. It should compare the implementation cost (including the design and investment cost, operational costs, and, if relevant, the economic value of any resources made available free of charge) with the results achieved (concerning the FLW prevented, the net economic benefits, the net environmental savings, the social benefits, and the outreach impact). **Sustainability of the Action over Time (EC4):** refers to a mitigation strategy's potential to be maintained over time and is only ensured if there is an organisational support for the action, an availability of financial and human resources, skills and knowledge, and a long-term strategic plan. **Transferability and Scalability (EC5):** refers to the degree to which the mitigation strategies have been transferred to different contexts or upscaled, or the degree to which these were considered in the design phase. **Intersectorial Cooperation (EC6):** assesses if the mitigation strategy results from the cooperation between different sectors of society and what their roles and responsibilities were within its implementation.

4.6.2 Phase II – Determining the relative weights of the evaluation criteria

The second phase of the framework proposed (Figure 4.1) uses fuzzy SWARA to determine the relative weights of the evaluation criteria defined beforehand. The second focus group discussion was important to enable the initialisation of this phase of the framework. During the second focus group discussion, the experts were asked to organise the evaluation criteria from the most to the least expected significance. After adjusting the organisation of the criteria, the experts were asked to judge the relative importance of each criterion, with the exception of the first one, based on the fuzzy evaluation scale presented in Table 4.4. After reaching a consensus, the $\hat{S}_j$ scores of each criterion were recorded and Eq. (5) to (8) were used to calculate the coefficient values, $\hat{k}_j$, the fuzzy recalculated weights, $\hat{q}_j$, the relative fuzzy weights, $\hat{w}_j$ and the relative defuzzified weights, w_j, of the evaluation criteria, respectively. Table 4.7 shows the results of fuzzy SWARA, showing that the Quality of the Action Design is the most relevant criterion to evaluate the mitigation strategies for FLW, followed by the Effectiveness, the Efficiency, the Sustainability of the Action over Time, the Transferability and Scalability and the Intersectorial Cooperation criteria.

Table 4.7 – Results of fuzzy SWARA to weight the evaluation criteria

	$\hat{S}_j$			$\hat{k}_j$			$\hat{q}_j$			$\hat{w}_j$			w_j
EC1	-	-	-	1,00	1,00	1,00	1,00	1,00	1,00	0,45	0,49	0,51	0,48
EC2	0,90	1,00	1,00	1,90	2,00	2,00	0,50	0,50	0,53	0,23	0,25	0,27	0,25
EC3	0,70	0,90	1,00	1,70	1,90	2,00	0,25	0,26	0,31	0,11	0,13	0,16	0,13
EC4	0,70	0,90	1,00	1,70	1,90	2,00	0,13	0,14	0,18	0,06	0,07	0,09	0,07
EC5	0,50	0,70	0,90	1,50	1,70	1,90	0,07	0,08	0,12	0,03	0,04	0,06	0,04
EC6	0,70	0,90	1,00	1,70	1,90	2,00	0,03	0,04	0,07	0,01	0,02	0,04	0,02

4.6.3 Phase III – Assessing and ranking suitable mitigation strategies

The third phase of the research framework proposed (Figure 4.1) uses the fuzzy WASPAS methodology to assess the performance of the mitigation strategies presented in Table 4.5, based on the relative weights of the evaluation criteria estimated in Phase II. The second discussion with the focus group was important to establish the DMM that enables the implementation of the fuzzy WASPAS methodology. To that end, the experts were asked to score how the mitigation strategies performed, for each evaluation criterion, using the scale from Table 4.4. The resulting fuzzy DMM is presented in Table 4.8. Afterwards, by following the steps mentioned in section 4.4.2, the values of Q_i, P_i, and K_i are calculated and the mitigation strategies are ranked. The intermediary calculations of the fuzzy SWARA method are provided in Tables B2, B3 and B4 of Appendix B. The ranking of the mitigation strategies for FLW is presented in Table 4.9.

Table 4.8 – Fuzzy WASPAS decision making matrix

	S01			S02			S03			S04		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,8	0,9	1,0	0,8	0,9	1,0	0,7	0,8	0,9	0,8	0,9	1,0
EC2	0,7	0,8	0,9	0,8	0,9	1,0	0,7	0,8	0,9	0,8	0,9	1,0
EC3	0,7	0,8	0,9	0,8	0,9	1,0	0,7	0,8	0,9	0,7	0,8	0,9
EC4	0,8	0,9	1,0	0,7	0,8	0,9	0,6	0,7	0,8	0,7	0,8	0,9
EC5	0,8	0,9	1,0	0,7	0,8	0,9	0,8	0,9	1,0	0,8	0,9	1,0
EC6	0,8	0,9	1,0	0,8	0,9	1,0	0,8	0,9	1,0	0,8	0,9	1,0

	S05			S06			S07			S08		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,8	0,9	1,0	0,8	0,9	1,0	0,8	0,9	1,0	0,8	0,9	1,0
EC2	0,8	0,9	1,0	0,8	0,9	1,0	0,7	0,8	0,9	0,8	0,9	1,0
EC3	0,8	0,9	1,0	0,6	0,7	0,8	0,8	0,9	1,0	0,8	0,9	1,0
EC4	0,8	0,9	1,0	0,5	0,6	0,7	0,6	0,7	0,8	0,8	0,9	1,0
EC5	0,8	0,9	1,0	0,8	0,9	1,0	0,5	0,6	0,7	0,8	0,9	1,0
EC6	0,8	0,9	1,0	0,8	0,9	1,0	0,4	0,5	0,6	0,4	0,5	0,6

	S09			S10			S11			S12		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,7	0,8	0,9	0,5	0,6	0,7	0,8	0,9	1,0	0,8	0,9	1,0
EC2	0,6	0,7	0,8	0,5	0,6	0,7	0,7	0,8	0,9	0,7	0,8	0,9
EC3	0,6	0,7	0,8	0,6	0,7	0,8	0,8	0,9	1,0	0,7	0,8	0,9
EC4	0,7	0,8	0,9	0,7	0,8	0,9	0,6	0,7	0,8	0,8	0,9	1,0
EC5	0,8	0,9	1,0	0,6	0,7	0,8	0,6	0,7	0,8	0,6	0,7	0,8
EC6	0,2	0,3	0,4	0,4	0,5	0,6	0,4	0,5	0,6	0,1	0,2	0,3

Table 4.8 – Fuzzy WASPAS decision making matrix (*continued*).

	S13			S14			S15			S16		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,8	0,9	1,0	0,7	0,8	0,9	0,7	0,8	0,9	0,6	0,7	0,8
EC2	0,7	0,8	0,9	0,7	0,8	0,9	0,6	0,7	0,8	0,6	0,7	0,8
EC3	0,7	0,8	0,9	0,7	0,8	0,9	0,3	0,4	0,5	0,4	0,5	0,6
EC4	0,7	0,8	0,9	0,5	0,6	0,7	0,4	0,5	0,6	0,5	0,6	0,7
EC5	0,3	0,4	0,5	0,6	0,7	0,8	0,6	0,7	0,8	0,6	0,7	0,8
EC6	0,7	0,8	0,9	0,5	0,6	0,7	0,7	0,8	0,9	0,2	0,3	0,4

Table 4.9 – Utility function values of the fuzzy WASPAS method and ranking of the mitigation strategies of FLW

	Q_i	P_i	K_i	Rank
S05	0,904	0,900	0,903	1
S08	0,894	0,887	0,893	2
S02	0,892	0,887	0,891	3
S04	0,883	0,878	0,882	4
S01	0,866	0,86	0,865	5
S06	0,855	0,845	0,853	6
S11	0,846	0,836	0,844	7
S07	0,842	0,831	0,840	8

	Q_i	P_i	K_i	Rank
S12	0,840	0,819	0,836	9
S13	0,834	0,821	0,832	10
S03	0,803	0,798	0,802	11
S14	0,780	0,773	0,778	12
S09	0,758	0,746	0,755	13
S15	0,698	0,675	0,694	14
S16	0,656	0,642	0,653	15
S10	0,632	0,625	0,631	16

4.6.4 Sensitivity Analysis

A sensitivity analysis is performed to assess the robustness of the results. This study performs 11 experiments. In experiments 1 to 6, we vary the values of the defuzzified relative weights of evaluation criteria (w_j), in Equation (3), to analyse the sensitivity of the fuzzy WASPAS method to the quality of criteria weights and, in experiments 7 to 11, we vary the values of λ in the utility function value (Eq. 18) of the fuzzy WASPAS method, to assess the sensitivity of the method to moving from WPM to WSM.

In the first 6 experiments, the evaluation criteria weights are assigned in a way such that one of the criterion has a higher weight and another the lowest weight, while the other criteria have weights distributed between the higher and the lower one, as suggested in Mishra et al. (2019) and Rani et al. (2020). Thus allowing us to illustrate a broader range of criteria weights to examine the sensitivity to the variation of the criteria weights of the approach proposed, efficiently and simply. The weight of each criterion in each of the sets is presented in Table 4.10. The fuzzy WASPAS method is applied to each set of criteria weights and the results of the sensitivity analysis based on varying the evaluation criteria weights are shown in Table 4.11. The values of λ are replaced by 0.0, 0.2, 0.5, 0.8 and 1.0 in experiments 7 to 11, to examine the sensitivity of the approach proposed to turn the WASPAS method into the WPM method ($\lambda = 0$), or into the WSM method (λ

= 1). The results of the sensitivity analysis based on varying the parameter λ are presented in Table 4.12.

Table 4.10 – Sets of criteria weights for sensitivity analysis

	EC1	EC2	EC3	EC4	EC5	EC6
Set 1	0,50	0,26	0,10	0,08	0,04	0,02
Set 2	0,02	0,50	0,26	0,10	0,08	0,04
Set 3	0,04	0,02	0,50	0,26	0,10	0,08
Set 4	0,08	0,04	0,02	0,50	0,26	0,10
Set 5	0,10	0,08	0,04	0,02	0,50	0,26
Set 6	0,26	0,10	0,08	0,04	0,02	0,50

Table 4.11 – Sensitivity analysis for various w_j values under fuzzy WASPAS

	Exp. 1		Exp. 2		Exp. 3		Exp. 4		Exp. 5		Exp. 6	
S05	0,900	1	0,900	1	0,900	1	0,900	1	0,900	1	0,900	1
S08	0,892	2	0,883	2	0,866	2	0,857	3	0,791	7	0,694	9
S02	0,888	3	0,882	3	0,864	3	0,824	5	0,848	6	0,894	2
S04	0,882	4	0,864	4	0,824	5	0,848	4	0,894	2	0,888	3
S01	0,864	5	0,824	5	0,848	4	0,894	2	0,888	3	0,882	4
S06	0,855	6	0,816	6	0,720	12	0,743	9	0,886	4	0,871	5
S11	0,841	7	0,796	8	0,790	7	0,701	11	0,677	11	0,664	12
S07	0,837	9	0,788	9	0,781	8	0,676	13	0,631	12	0,671	11
S12	0,839	8	0,776	10	0,763	9	0,760	8	0,588	15	0,503	15
S13	0,832	10	0,768	11	0,761	10	0,697	12	0,602	14	0,817	7
S03	0,798	11	0,802	7	0,791	6	0,785	6	0,874	5	0,848	6
S14	0,775	12	0,763	12	0,721	11	0,653	14	0,693	10	0,689	10
S09	0,757	13	0,710	13	0,714	13	0,764	7	0,694	9	0,522	14
S15	0,701	14	0,603	16	0,502	16	0,600	15	0,718	8	0,741	8
S16	0,659	15	0,613	15	0,525	15	0,592	16	0,572	16	0,461	16
S10	0,627	16	0,649	14	0,701	14	0,714	10	0,626	13	0,558	13

Table 4.12 – Sensitivity analysis for various λ values under fuzzy WASPAS

	Exp. 7		Exp. 8		Exp. 9		Exp. 10		Exp. 11	
S05	0,900	1	0,900	1	0,902	1	0,903	1	0,904	1
S08	0,887	3	0,888	2	0,891	2	0,893	2	0,894	2
S02	0,887	2	0,888	3	0,890	3	0,891	3	0,892	3
S04	0,878	4	0,879	4	0,881	4	0,882	4	0,883	4
S01	0,860	5	0,861	5	0,863	5	0,865	5	0,866	5
S06	0,845	6	0,847	6	0,850	6	0,853	6	0,855	6
S11	0,836	7	0,838	7	0,841	7	0,844	7	0,846	7
S07	0,831	8	0,833	8	0,837	8	0,840	8	0,842	8
S12	0,819	10	0,824	9	0,830	9	0,836	9	0,840	9
S13	0,821	9	0,823	10	0,827	10	0,832	10	0,834	10
S03	0,798	11	0,799	11	0,800	11	0,802	11	0,803	11
S14	0,773	12	0,774	12	0,776	12	0,778	12	0,780	12
S09	0,746	13	0,748	13	0,752	13	0,755	13	0,758	13
S15	0,675	14	0,680	14	0,687	14	0,694	14	0,698	14
S16	0,642	15	0,645	15	0,649	15	0,653	15	0,656	15
S10	0,625	16	0,626	16	0,628	16	0,631	16	0,632	16

Spearman's correlation coefficient (ρ) is used to assess the changes in the rankings of the mitigation strategies. This coefficient measures the strength of the relationship between two variables (Table 4.13) and the closer its value is to 1, the stronger the relationship and the similarity between rankings. Spearman's correlation coefficient compares the positions of the 16 mitigation strategies in the rank for the different experiments. Table 4.14 shows the correlation coefficients between the experiments that vary the evaluation criteria weights. All relationships presented in the table are either very strong (values greater than 0.8) or strong relationships (values between 0.6 and 0.8). In other words, varying the criteria weights does not have a high impact on the rankings of the mitigation strategies. Table 4.15 shows the correlation coefficients between the experiments that vary the λ parameter. All relationships presented in the table are very strong, which implies that varying the value of λ has very little impact on the ranks of the mitigation strategies. Therefore, it can be concluded that the results of the proposed fuzzy WASPAS approach are stable when either the criteria weights or the λ parameter are varied.

Table 4.13 – Interpretation of Spearman's correlation coefficient (Keshavarz-Ghorabaee et al., 2020)

Range of the coefficient	Interpretation of Relationship
$\rho \geq 0{,}8$	Very strong
$0{,}6 \leq \rho < 0{,}8$	Strong
$0{,}4 \leq \rho < 0{,}6$	Moderate
$0{,}2 \leq \rho < 0{,}4$	Weak
$\rho < 0{,}2$	Very weak

Table 4.14 – Spearman's correlation coefficient between experiments 1 to 6

	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6
Exp. 1	1	0,956	0,891	0,762	0,650	0,682
Exp. 2	0,956	1	0,935	0,835	0,724	0,726
Exp. 3	0,891	0,935	1	0,812	0,594	0,632
Exp. 4	0,762	0,835	0,812	1	0,735	0,606
Exp. 5	0,650	0,724	0,594	0,735	1	0,853
Exp. 6	0,682	0,726	0,632	0,606	0,853	1

Table 4.15 – Spearman's correlation coefficient between experiments 7 to 11

	Exp. 7	Exp. 8	Exp. 9	Exp. 10	Exp. 11
Exp. 7	1	1	0,994	0,994	0,994
Exp. 8	0,994	1	1	1	1
Exp. 9	0,994	1	1	1	1
Exp. 10	0,994	1	1	1	1
Exp. 11	0,994	1	1	1	1

4.6. Results

Sixteen mitigation strategies for FLW were selected by the experts to be prioritised to apply and test the framework in the Portuguese FVSC. The mitigation strategies selected seem to fall into four different categories (Table 4.5): (1) Information – strategies that improve the information flow throughout FSCs and the availability of data to ensure better decision making (S01 to S07); (2) Quality – strategies to improve the control and the standardisation of the processes (S08 to S12); (3) Technology – strategies that implement new technologies to reduce FLW (S13 and S14); and (4) Transport and Infrastructures – strategies related to improving infrastructures and transportation systems (S15 and S16).

The results from the fuzzy SWARA method (Table 4.7) showed that the Quality of the Action Design (EC1), with a relative weight of 48.4%, is the most important criterion to satisfy to ensure the viability of a mitigation strategy and to maximise its impact on FLW reduction. A bad quality action design can compromise its Effectiveness (EC2) and Efficiency (EC3) (De Laurentiis, Caldeira and Sala, 2020). Therefore, it is not surprising that these two criteria were considered the second and the third most important evaluation criteria, with weights of 24.7% and 13.3%, respectively. The Sustainability of the Action over Time (EC4), with a weight of 7.2%, the Transferability and Scalability (EC5), with 4.4%, and the Intersectorial Cooperation (EC6), with 2.4%, have significantly lower weights, but still influence the ranking of the mitigation strategies. This is exactly what was concluded from the sensitivity analysis shown in Table 4.11. Varying the weights of the evaluation criteria fed into the fuzzy WASPAS method has some influence over the final ranking, especially when we assign higher weights to criteria EC5 and EC6. There are some dissimilarities between the outcomes reached in different experiments, even between the top 5 ranked mitigation strategies. However, Spearman's correlation coefficient (Table 4.14) shows that the relationships between the different experiments are strong at the least and very strong at the best, showing that the final outcome is sound and robust and not that different from what it would be with other relative weights assigned to the evaluation criteria.

The final ranking of the mitigation strategies determined by the fuzzy WASPAS method (Table 4.9) was as follows: "Share and maintain information regarding the remaining shelf life" (S05) was the highest priority, followed by "Training staff on handling practices" (S08), "Ensure communication among FSC stages" (S02), "Implement automated demand forecasting systems" (S04), "Develop and use intelligent packaging to monitor products' safety and quality" (S01), "Improve visibility along FSCs through traceability systems" (S06), "Correct date marking to avoid confusion" (S11), "Find new markets for overproduction or products sorted out due to industry's quality standards" (S07), "Invest in more and regularly maintain storage facilities" (S12), "Develop new packaging and preservation techniques to enhance the product's shelf life" (S13), "Implement integrated IT systems throughout FSCs" (S03), "Improve cooling methods"

(S14), “Ensure adherence to standard procedures” (S09), “Improve transport infrastructures” (S15), “Improve the means of transportation” (S16), and, finally, “Adjust packaging size” (S10).

Table 4.6 shows that the most promising mitigation strategy to reduce FLW in the Portuguese FVSC (S05) should be implemented from post-harvest handling and storage until the retail stage of the FVSC and directly tackles: inadequate demand forecasting (C1), the overproduction and excessive stock (C2), the non-conformances to retail specifications (C6), the sensorial or microbial deterioration (C7), the short shelf life or expired products (C8), the pricing strategies and promotions management (C11), the lack of coordination and information sharing (C12) and the inefficiency of in-store management (C14). The second highest performing mitigation strategy (S08) should be implemented at all stages of the FVSC (agricultural production, post-harvest handling and storage, processing and packaging, distribution and retail) potentially eliminating the staff’s poor handling and operational performance (C3) and the product’s non-conformances to retail specifications (C6). S02 and S04, the third and fourth ranked mitigation strategies, should be implemented at all stages of the FVSC and can help to solve the: problem of inadequate demand forecasting (C1), overproduction and excessive stock (C2), pricing strategies and promotions management (C11), and the lack of coordination and information sharing (C12). S02 can also solve the storage at the wrong temperature (C4). The fifth highest priority mitigation strategy, S01, should be implemented from the processing and packaging stage of the FVSC until retail and could overcome the FLW caused by storage at the wrong temperature (C4), inadequate or defective packaging (C5), non-conformance to retail specifications (C6), sensorial or microbial deterioration (C7), short shelf life or expired products (C8), a lack of coordination and information sharing (C12) and inefficient in-store management (C14). In other words, if the five mitigation strategies with higher priorities were implemented in FVSCs, approximately 80% of the causes of FLW identified would have been dealt with, leaving only the FLW caused by climate change and weather variability (C9), the lack of storage facilities (C10) and the inadequate transportation systems (C13).

Overall, the mitigation strategies with highest priorities are more transversal to the FVSC (Table 4.6) and belong to the category of Information (Table 4.5), with the exception of the second-ranked mitigation strategy (S08 – Training staff on handling practices) that is a Quality-related mitigation strategy. This is an expected outcome, since the mitigation strategies that should be applied more transversely to the FVSC are the ones most closely related to the communication along the stages of FSCs, to improve information sharing and the visibility of data through traceability systems and implement integrated systems that could ensure automated demand forecasting throughout FSCs.

4.7. Discussion

Finding out which mitigation strategies should be implemented to reduce FLW in FSCs is quite challenging, considering that there are numerous factors influencing the performance of the mitigation strategies. The research framework proposed in this paper makes this process a systematic and understandable one. The results previously presented support some evidences that had been provided in the literature, mainly regarding the importance of information sharing regarding FLW reduction. Rodrigues et al. (2020) concluded that information processing and information sharing ensured the reduction of FLW in an online FSC business environment and that quality and product performance policies can greatly influence the generation of FLW throughout FSCs. Previously, Göbel et al. (2015) had concluded that improving communication and information sharing among all stakeholders of the German FSC could potentially lead to a more sustainable food system, since insufficient cooperation across FSCs was leading to an exacerbated generation of FLW, because each member of FSCs was optimising only his or her own processes and there were no joint efforts concerning avoiding FLW. In fact, Mohammadi et al. (2019) proved that a coordinated approach, where an incentive mechanism is proposed to guarantee more profitability for the whole FSC system, was able to achieve greater FSC coordination and convince members to make globally optimum decisions that not only increased profit along the whole FSC, as well as individual members', but also significantly reduced the global level of FLW. Information sharing is positively related to supply chain coordination (Li *et al.*, 2019) and both can help to solve the information-related issues along FSCs.

Certain mechanisms may be employed to ensure coordination along FSCs. Handayati et al. (2015) described four different types of coordination mechanisms: supply chain contracts, information sharing, joint decision-making and collaborative learning. The most common coordination mechanism is the supply chain contract and is used to manage supplier and buyer relationships and to manage risk along FSCs. Several parameters (such as the type of crops to grow, delivery dates, etc.) are clearly specified in the contract to ensure that farmers can fulfil the buyer’s demand. Rewards or penalties are usually stated as incentives and can be included in the contract to solve conflicts of interest among the members of FSCs, making sure that all members are focused on the final costumer and on the total profit (Handayati, Simatupang and Perdana, 2015). Information sharing is useful to avoid any data distortion in the chain. Sharing information related to demand, orders and inventory, for instance, allows the members of FSCs to coordinate with one another, leading to an improvement in FSCs’ performance (Handayati, Simatupang and Perdana, 2015). Basically, these mechanisms are used to harmonise the relationships between the members of FSCs and to solve any potential conflicts of interest. More recently, Kramer et al. (2021) investigated the effects of implementing blockchain technology on coordination mechanisms in agri-food networks and referred to two more coordination mechanisms: exerting power and building routines. Power can shift between the members of the network and roles can change depending on the tasks and the relationships, while creating routines can be used to enhance the individuals' understanding of the overall process and their role in it. Apart from these mechanisms, voluntary agreements between the members of FSCs can also be used to set, monitor, and achieve resource efficiency and FLW reduction targets, while conciliating the role of each stakeholder and incentivising knowledge sharing concerning best practices (Simone et al., 2018).

Furthermore, ensuring coordination between FSC members and promoting their close collaboration can also help to implement the technologically related mitigation strategies identified in Table 4.5. In fact, Ciccullo et al. (2021) thoroughly investigated the range of technologies available and their contribution to FLW prevention (e.g., forecasting, monitoring, shelf life extension) and concluded that technological innovations, like the implementation of traceability systems or new technological infrastructures to support information exchange are all reliant on an appropriate collaborative environment. The results reported by Kleineidam (2020), who identified the fields of action most frequently mentioned to reduce FLW within logistics networks, are significantly aligned with our results, showcasing the increase of transparency both within and between companies, and the improvement of quality management, for the early detection of weaknesses, as the most important fields of action to optimise the process and reduce FLW.

Even though the experts consider the information-related strategies more relevant to reduce FLW along the FVSC, "training staff on handling practices" (S08) appears in the mix of these information-related strategies in the second place, because we are dealing with fresh fruits and vegetables that are very fragile and highly perishable food products, which are more prone to deterioration due to mishandling during their movement along the FVSC. This leads to the conclusion that the framework presented here should be replicated for other FSCs, since the intrinsic characteristics of the food products may play a role concerning the ranking of the performance of the mitigation strategies concerning the reduction of FLW. The strategies that are lower in the rank are related with transportation and improvements in infrastructures due to this study's geographical context. Portugal has great rail, road, airport, and seaport infrastructures, with the quality of its infrastructures ranking 23rd globally, according to the 2018 Logistics Performance Index from the World Bank (Arvis et al., 2018). However, inefficient transportation networks and the poor transportation planning are still inhibitors that must be overcome in developing countries (Gokarn and Kuthambalayan, 2017; Kuyu et al., 2019), where the Transport and Infrastructure-related mitigation strategies could potentially play a more relevant role in reducing FLW. This shows that one must be careful when generalising the results of this study and highlights the need to apply our framework to other economic contexts, in order to identify and prioritise mitigation strategies in these situations.

This study makes several theoretical and managerial contributions. Theoretically, this paper expands the existing body of literature by answering the aforementioned research question in the introduction section. Twenty potential strategies to reduce FLW in FVSCs were identified, from which sixteen were found relevant for the Portuguese FVSC, according to the opinion of the group of experts. This study ranked the strategies selected by the experts according to their performance under the evaluation criteria, prioritizing the strategies closely related to information and emphasizing the role of communication along the stages of the FVSC to reduce FLW, by means of the improvement of the information sharing and the visibility of data between stages, through traceability systems, and of the implementation of integrated systems that could ensure automated demand forecasting throughout the FVSC. Moreover, previous studies seldom identified the mitigation strategies to reduce FLW along FSCs and have not considered the entire FVSC or a developed country like Portugal.

For managers, understanding the performance of the mitigation strategies under a set of evaluation criteria allows them to better prioritise the different strategies. Our findings provide guidance towards the prioritisation of the mitigation strategies, showing a feasible way to select and enable the implementation of the most promising mitigation strategies for FLW. In general, this paper provides a framework that managers can replicate in any business or supply chain to select and prioritise cost effective mitigation strategies with higher environmental and social gains. The framework can further be tailored to different evaluation criteria, depending on the main goals that managers want to fulfil or on their business conditions (like the available budget to allocate towards the reduction of FLW).

4.8. Conclusion

An evaluation research framework, combining fuzzy SWARA and fuzzy WASPAS was developed to prioritise the mitigation strategies for FLW resulting in a valuable contribution towards the body of knowledge on FLW, in this study. An important strength is that it is a first attempt to identify, evaluate and prioritise potential mitigation strategies for FLW. This research also reveals how the different mitigation strategies for FLW perform under a set of evaluation criteria, providing researchers, practitioners and policymakers with a comprehensible and structured approach to prioritise cost effective efforts with higher environmental and social gains.

The findings revealed that 16 mitigation strategies had the potential to tackle the relevant causes of FLW in the Portuguese FVSC. The fuzzy SWARA method revealed that the “quality of the action design”, the “effectiveness” and the “efficiency” criterions were the ones that most influenced each mitigation strategy’s potential to reduce FLW and the fuzzy WASPAS method ranked the 16 strategies studied. This ranking showed that the five strategies that should be implemented first to reduce FLW are: (1) sharing and maintaining information regarding the remaining shelf-life of a product; (2) training staff on handling practices; (3) ensuring communication among FSC stages; (4) implementing automated demand forecasting systems, and (5) developing and using intelligent packaging to monitor products' safety and quality. These strategies are mainly categorised as information-related strategies, which improve the information flow along FSCs to ensure that the decision-making process is supported with sufficient information. Sharing this information might minimise the mismatch between supply and demand and improve the decisions taken related to a product’s shelf life. It also highlights the role of information management in the reduction of FLW along the Portuguese FVSC. These findings answered the research question that guided this paper.

Despite the contributions stated above, it is essential to acknowledge the limitations of this study. One is related to the research framework’s dependency on the opinions of experts. It is vital to be very careful when collecting the experts’ opinions. Another limitation is the generalisation of the results. Even though the results from this research may be generalised to other developed countries, with similar causes of FLW to those verified in the Portuguese FVSC, researchers could and should replicate the research methodology proposed in different regions or FSCs to determine the most promising mitigation strategies to reduce FLW in those contexts. After all, FLW occurs globally along global FSCs and improving the local FSC can contribute to optimising FSCs at a global scale (Ali et al., 2019). Further, the evaluation criteria selected for this study greatly influenced the performance assessment of the mitigation strategies. The criteria used in this study were found to be the most appropriate within the context of the Portuguese FVSC, but other criteria should be considered to prioritise the mitigation strategies for FLW and further investigate the influence of the criteria on the ranking of strategies. Another avenue for future work is to implement the highest priority mitigation strategies and then assess the efficiency and effectiveness of those strategies empirically to evaluate their real potential to reduce FLW. This would validate empirically the research framework proposed for the Portuguese FVSC to fully test whether the current framework can prioritise the mitigation strategies for FLW appropriately. Instead of testing these implementations empirically, system dynamics or agent-based modelling could be employed to model the FVSC and assess the resulting changes in the FLW flow along the supply chain for different mitigation strategies, thereby assessing the validity of the research framework presented here.

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CONCLUSION

Although the FLW issue has been studied for a while now (there are studies published in peer-reviewed journals that date back to the 1920s), there has been a noticeable increase in publications in the last decade, which has increased the awareness of global entities concerning this problem and has improved the overall knowledge we have about FLW. However, there are still some inconsistencies and uncertainties regarding the body of knowledge on FLW, since the problem has been studied from many perspectives using an array of different frameworks and methodologies. In spite of these inconsistencies and uncertainties, global researchers, stakeholders and public policy-makers seem to agree that FLW is a pressing issue to tackle in order to contribute to a sustainable food system. Therefore, addressing the phenomenon of FLW along FSCs is a societal and environmental responsibility and this thesis is the result of a desire to take on this responsibility and to contribute to this discussion. Since there is still a need to increase knowledge concerning the FLW problem, and it is known that this problem is not specific to one stage of FSCs, meaning that tackling the problem at one stage may even create a new problem at another stage of a particular FSC, this thesis maintains a holistic approach to the issue and studies the phenomenon of FLW from a supply chain perspective.

The main goal of this thesis was to find a way to determine the most promising strategies to mitigate the FLW problem along FSCs. This study starts by exploring the phenomenon of FLW, with the objective of understanding all aspects of this complex issue and all the perspectives from which it had been previously studied. Thus, the existing literature about FLW is thoroughly analysed in Chapter 1. The systematic literature review presented in Chapter 1 demonstrates the complexity of the FLW phenomenon along FSCs and highlights the extent and current relevance of this issue. The chapter summarised the multiplicity of causes that generate FLW and the variety of mitigation strategies that are referred to in the literature to reduce FLW along FSCs. This helped to explain the growing number of studies concerning this issue and why there is still a lack of knowledge about the strategies that need to be implemented within businesses and at the supply chain level to reduce FLW to an acceptable minimum level.

The main findings in Chapter 1 answer the first research question that guided this thesis (*What are the main causes of FLW at the different stages of FSCs, for economies at different levels of development and for different food products?),* indicating that, in developing countries, FLW occurs essentially at the earlier stages of FSCs. This is due to the lack of infrastructures and associated technical and managerial skills in food production and post-harvest processing. FLW arises mostly at the downstream stages in developed countries, due to a lack of coordination and communication between the different members of FSCs and the consumers' behaviour. Both developed and developing countries have problems with the time in-transit and with the interruptions of the cold chain that compromise the quality of the food products. However, developing countries still face basic issues regarding the lack and inadequacy of their infrastructures. Moreover, it was concluded that most causes of FLW are dependent on the stage of the particular FSC analysed and also on the food product and differ between developed and developing countries. Chapter 1 also provided an answer to the second research question of this thesis (*Which mitigation strategies help to reduce FLW at the different stages of FSCs, for economies at different levels of development and for different food products?*). It is concluded that, for developed countries: the implementation of technological solutions, the development of new markets/outlets and new ways to sell/redistribute sub-standard products; as well as the improvement of the in-store management and, on a higher scale, of the supply chain management (through the enforcement of coordination and information sharing mechanisms between stakeholders), show great potential to reduce FLW along FSCs. For developing countries, on the other hand, the strategies with most potential seem to be linked to the improvement of infrastructures and to the dissemination of good practices between stakeholders. In this case, it was concluded that the mitigation strategies of FLW are also dependent on the level of economic development, on the stage of FSCs and on the food product.

Moreover, from the main findings reported and the opportunities for future research highlighted in Part I, it was also possible to develop a research framework to guide future investigations seeking to study FLW and to investigate the most promising strategies to mitigate FLW along FSCs. This study is one of the first attempts to develop such a framework. The 8-step framework developed in Chapter 2 consists of: (1) setting the system's boundaries and the context of the problem; (2) defining FLW; (3) estimating the levels of FLW along the FSC or FSCs under study; (4) identifying the causes leading to the generation of FLW; (5) assessing the interrelationships between causes and determining the root causes of FLW; (6) identifying potential mitigation strategies to tackle the root causes and define evaluation criteria to assess the strategies' performance; (7) ranking the mitigation strategies of FLW according to their performance; and (8) estimating the strategies' efficiency to reduce FLW and assessing the impact on the FSC or FSCs; identifying redesign strategies, if necessary.

The conclusions of Part I guided the development of the empirical part of the thesis, corresponding to Part II. The suitability and validity of steps 4 and 5 of the research framework to identify and model the relationships between the causes of FLW to determine the root causes for the scenarios under study, was tested empirically in Chapters 2 and 3. Further, the appropriateness of steps 6 and 7 to identify, evaluate and rank the mitigation strategies of FLW were empirically tested in Chapter 4 of this thesis. Steps 4 and 5 of the research framework were tested in two different scenarios, corresponding to the fruit and vegetable supply chain in Portugal and to the beef supply chain in Brazil. This was done to assess the validity of the framework to determine the root causes of FLW for countries with different levels of economic development and for different food products.

In Chapter 2, the interrelationships between the causes of FLW were analysed in the context of the fruit and vegetable supply chain in a developed country, namely Portugal. Fourteen causes of FLW were identified and categorised into logistic-, quality- and retail-related causes, according to their nature. These were then modelled through an ISM-MICMAC approach showing that logistic-related causes were the most influential causes of FLW in the scenario studied. They also significantly influenced the causes related to quality and retail. Indeed, all the root causes of FLW were logistic related. Another relevant finding was that the root causes of FLW were transversal to all or almost all stages of the FVSC, emphasising the need to study FLW from a supply chain perspective and to implement mitigation strategies at the supply chain level to enable the reduction of FLW all along the FVSC, and not only at a particular stage. This chapter shed light on the influence that the relationships between the causes of FLW can have for the selection or design of suitable mitigation strategies of FLW. The findings from this chapter helped to answer the third research question that guided this thesis (*How are the causes of FLW along fresh food supply chains interrelated?*).

The interrelationships between the causes of FLW are further explored in the context of the beef supply chain in Brazil in Chapter 3. Sixteen causes of FLW were identified and categorised into logistic, product and demand related causes, according to their nature. These were then modelled through an ISM-MICMAC approach showing that, unlike the previously studied scenario, the most influential causes of FLW included causes from all three of the natures identified. Despite the fact that some of the root causes of FLW identified were somewhat similar to the ones identified in the Portuguese fruit and vegetable supply chain scenario (for instance, both FSCs struggled with logistic related issues like poor handling and operational performances or even transportation inefficiencies), other root causes of very different natures were also identified in the Brazilian beef supply chain. These included the variety of the products available in the supermarkets (which is a demand related cause of FLW) and unhealthy animals and the outbreak of diseases (which is a product related cause of FLW). Overall, besides helping to answer the second research question, Chapter 3 validates the research framework developed in Chapter 1 for different regions and for different food products, emphasising the importance of having a framework that can successfully identify the root causes of FLW and the way the causes of FLW are interrelated in different scenarios.

The results of Chapter 2 provided the necessary background to carry on with the study in Chapter 4. This chapter is one of the earliest attempts to identify, evaluate and prioritise potential mitigation strategies for FLW from a supply chain perspective. The mitigation strategies of FLW that could tackle the causes of FLW previously determined for the fruit and vegetable supply chain, in Chapter 2, were identified and then prioritised according to the strategies' performance under a set of evaluation criteria. The chapter's main findings include the identification of 16 mitigation strategies to tackle the relevant causes of FLW in the scenario under analysis. These were divided into: information, quality, technology, and transport and infrastructure related strategies, according to their nature. Afterwards, a set of evaluation criteria was assessed using the fuzzy SWARA method to estimate their relative weights to estimate each of the strategies' performances, which was made possible using the fuzzy WASPAS method. The ranking determined by the fuzzy WASPAS method showed that the higher ranked strategies that should be implemented first to reduce FLW were mainly information-related strategies that improved the information flow along FSCs to ensure that the decision-making process is supported by sufficient and real-time information, minimising the mismatch between supply and demand, and improving the decisions related to the product's shelf life. These findings further highlighted the role of information management in the reduction of FLW along the fruit and vegetable supply chain in Portugal and answered the fourth research question that guided this thesis (*How should the most promising mitigation strategies of FLW to tackle the known causes of FLW and reduce FLW along fresh food supply chains be identified, evaluated and prioritised?*).

Apart from presenting the main conclusions of the thesis, this chapter also highlights the contributions it makes to theory and practice, the limitations of the study and some recommendations for future research.

i. Contributions to Theory

In achieving the research objectives and answering the research question, this thesis provides several contributions to the body of knowledge concerning the study of the phenomenon of FLW. Part I of the thesis contributes to the literature, since it clearly presents what is already known and what needs to be further discussed and investigated concerning the topic of FLW along FSCs. The systematic literature review revealed several aspects that are still not widely explored, such as the way that the causes of FLW are interrelated and how this knowledge is of upmost importance to guide the selection of the most promising strategies to mitigate FLW along FSCs. Chapter 1 contributes to the state of the art on FLW by summarising the causes and mitigation strategies of FLW for the different stages of FSCs, for countries with different levels of economic development and for different food products, thereby increasing knowledge on the matter. In particular, this study does not focus on smaller, specific parts of FSCs, and maintains a holistic perspective of the problem under study. This thesis analyses what happens from production to retail and during transportation in between stages to ensure a supply chain perspective of the problem. Furthermore, the first part of the thesis finishes with another contribution to theory by leaving a research framework that researchers should implement in the future to determine the most promising mitigation strategies to reduce FLW along FSCs, for any given context.

Part II provides several contributions to theory, since it addresses the topics that were studied previously empirically. Chapters 2 and 3 provide a methodology that researchers can replicate in any context and for different food products to identify and model the interrelatedness between the causes of FLW. Chapter 2 increases the knowledge available concerning the causes of FLW by determining its root causes in the fruit and vegetable supply chains in Portugal, by analysing of the interrelationships between the relevant causes of FLW identified. Chapter 3 adds to the knowledge on the causes of FLW by replicating this procedure for the beef supply chain in Brazil. Even though the causes of FLW had been analysed by several authors (Mena et al., 2011; Buzby and Hyman, 2012; Kolawole et al., 2021), few have assessed the way the causes are interrelated and how those relationships influence the generation of FLW. Furthermore, Chapter 3 contributes to the literature by identifying a new cause of FLW in the Brazilian beef supply chain that had not been reported before, which concerns the lack of standardisation of the different cuts of beef that leads to unnecessary trims and, consequently, to FLW. Chapter 4 contributes to the literature concerning the mitigation strategies of FLW, by providing a framework that researchers can replicate in any context to identify, evaluate and rank the potential mitigation strategies to reduce FLW along FSCs. This chapter further contributes to theory by adding to the literature concerning the mitigation strategies of FLW by identifying of the strategies that can potentially tackle and mitigate the causes of FLW identified in the fruit and vegetable supply chain in Portugal. Furthermore, the mitigation strategies are evaluated and ranked to enable the selection of the most promising strategies to be implemented in order to reduce FLW in this supply chain. Moreover, the results of this chapter contribute to the literature by showing that the mitigation strategies that are more transversal to the supply chain and related to the flow of information along FSCs, should be prioritised. This emphasises the role of communication between the stages of FSCs to reduce FLW, by improving the information sharing and the visibility of data between stages. Tracing systems and the implementation of integrated systems could ensure automated demand forecasting throughout FSCs. Even though only a few studies in the literature have investigated the influence of information sharing and coordination on the performance of FSCs, they have pointed out the positive relation between the implementation of certain mechanisms and the reduction of FLW. Unfortunately, these strategies have often been overlooked in the studies that ranked preventive measures of FLW and a comparison between the performance of these strategies and other purely technological strategies have been seldom investigated.

ii. Contributions to Practice

From the analysis of the literature regarding FLW, the first part of the thesis contributes to practice by providing valuable information for managers concerning decision making regarding the implementation of strategies to reduce FLW along FSCs. Based on the most important research in the field, Chapter 1 summarises and presents the causes and the mitigation strategies of FLW for the different stages of FSCs, for developed and developing countries and for plant-based and animal-based supply chains. This additionally provides managers with a framework that can help to: estimate the levels of FLW, identify the causes of FLW and identify the most promising strategies to mitigate FLW within their businesses or supply chains.

The aim of Part II of this thesis is to test the suitability of steps 4 to 7 of the framework developed in Part I to model the interrelatedness between the causes of FLW in order to identify the root causes, and, consequently, the mitigation strategies to tackle FLW and prioritise them according to their potential to reduce FLW along FSCs. Chapter 2 and 3 provide valuable insights for practitioners, by testing the applicability of steps 4 and 5 of the framework to identify the main causes of FLW in the Portuguese fruit and vegetable supply chain (Chapter 2) and in the Brazilian beef supply chain (Chapter 3) and by revealing the nature of the interdependent relationships between the causes of FLW. The knowledge concerning which causes are more influential for the generation of FLW may be used to guide practitioners in the design of policies to facilitate the mitigation and prevention of FLW effectively, highlighting the need to prioritise the allocation of resources and efforts to address these causes. Moreover, these chapters provide a methodology that managers can replicate in any other scenario to understand the interrelatedness between the causes of FLW and identify the root ones.

In Chapter 4, the applicability of steps 6 and 7 of the framework was tested in the Portuguese fruit and vegetable supply chains to understand which mitigation strategies can address the main causes of FLW identified in Chapter 2, providing managers with information about which strategies should be prioritised. Furthermore, Chapter 4 provides a valuable methodology that managers can replicate to choose and develop cost effective mitigation strategies with higher environmental and social gains for any specific context. Understanding the performance of the mitigation strategies under different evaluation criteria allows practitioners to prioritise the different strategies better. In this sense, managers can choose different evaluation criteria according to the main objectives they need to achieve and, taking into consideration their business circumstances, prioritise the different mitigation strategies according to their performance in relation to those criteria.

iii. Limitations

This thesis has some limitations, especially related to the methods adopted. The main limitation of Part I is related to the subjectivity of the selection of articles for analysis. Although a systematic literature review methodology tries to minimise this limitation, the assessment of each article is still a subjective process. The ISI Web of Science and the SCOPUS databases were used to identify the most important studies on the field. Although these are two of the most important databases in the field and have been used in the selection process in previous studies, it is possible that some important works may not have been included. Additionally, the criteria used to select the articles might have excluded relevant studies, since conference proceedings, book chapters and even articles published in languages other than English were not considered. The keywords and strings used to search for relevant articles in the databases could also represent a source of bias.

The main limitation of Part II of this thesis concerns the methods applied, especially related to data collection. The ISM methodology and MICMAC analysis (from Chapters 2 and 3) and the SWARA and WASPAS methodologies (from Chapter 4) relied on focus group discussions and semi-structured interviews to collect the opinion of experts and enable the implementation of the methodologies. The experts that were part of this study represented the fruit and vegetable supply chains in Portugal and the beef supply chain in Brazil. The results and conclusions of these chapters should be interpreted with caution, since the generalisation of the results to other geographical regions or to other food products may not be straightforward, given that these chapters rely on qualitative assessments. However, to minimise this limitation, the chapters incorporate a broad discussion comparing the findings of this thesis with previous literature to highlight the relevance of its findings.

Another limitation concerns the lack of empirical data to support the test of steps 3 and 8 of the research framework presented. The third step, corresponding to the assessment of the levels of FLW for the contexts under study, was skipped in this thesis due to the lack of available data to allow the quantification of the levels of FLW along the fruit and vegetable supply chain in Portugal and along the beef supply chain in Brazil. Without the implementation of the third step of the research framework and due to the lack of data availability, it was impossible to investigate what impact the implementation of the mitigation strategies would have on FSCs. This also precludes the assessment of the performance of FSCs and of the efficiency of the mitigation strategies to reduce the levels of FLW along FSCs.

Moreover, the growth of publications relating to FLW during the past years may undermine the purpose of this thesis. During the last five years, the number of scientific peer-reviewed publications has increased significantly, offering new points of view and important discussions on the matter. Despite that, this thesis is still relevant and innovative, filling the gaps in the previous literature and contributing to the current debate on FLW. In fact, recent publications have reinforced the thesis' objectives and further contributed to the discussion of our findings.

iv. Recommendations for Future Work

Several recommendations for future research have emerged from the chapters of this thesis. The recommendations for future research in Chapter 1 highlight the need to identify the root causes of FLW, for different supply chains and food products, and to assess the causes' interdependencies, to fully understand the influence they have over each other and ultimately over the generation of FLW, thus identifying the ones that are more critical to be mitigated. It also mentions that there is a need to investigate the effectiveness of the mitigation strategies of FLW further in order to understand to what extent FLW is preventable along FSCs.

In the second part of the thesis, Chapters 2 and 3 make similar recommendations for future research. First, the research methodologies developed and implemented in those chapters should be replicated for other geographical contexts to assess the influence that different supply chain dynamics have on the relationships between the causes of FLW. The research methodologies should also be replicated for other food products, to evaluate how different the relationships between the causes would be, and the consequences this would have on the identification of the most suitable mitigation strategies. Secondly, both chapters refer to the need for more research regarding the mitigation strategies of FLW, particularly investigating the procedure that should be followed to make sure we select and implement the most appropriate mitigation strategies for FLW and also investigate the effectiveness of these strategies to reduce FLW, since the existing literature is mainly theoretical and does not account for, or measure, the real impact each strategy has on the level of FLW along FSCs. Moreover, Chapter 3 suggests that the model presented should be validated statistically using structural equation modelling (SEM) and a large-scale survey could be used for post-hoc validation to generalise the results.

Chapter 4 states that future research should replicate the research methodology for different regions, supply chains or food products to improve knowledge concerning the mitigation strategies of FLW and to determine the most promising strategies to reduce FLW in other contexts. Additionally, future works should use different evaluation criteria to evaluate the performance of the mitigation strategies, this would enable the influence of these criteria on the ranking of the strategies to be analysed. In the future, the higher-ranking strategies determined in Chapter 4 should be implemented to assess their efficiency and effectiveness in reducing FLW empirically and to validate the research framework proposed. As a final recommendation, and as a large amount of empirical data that is often not available would be necessary, future studies could use simulation to model the fruit and vegetable supply chain, assess the changes in the flow of FLW along the supply chain and estimate the strategies' efficiency and effectiveness to reduce FLW.

Moreover, even though the third and the eighth step of the research framework were not tested within the timeline of this thesis, these steps could be carried out in the near future, based on data from the literature and using simulation to model the fruit and vegetable supply chain, to estimate the levels of FLW along the supply chain, assess the mitigation strategies' efficiency and effectiveness to reduce FLW and ultimately assess the suitability of the research framework as a whole to guide future investigations in the identification of the most promising mitigation strategies to implement in any particular scenario. Thus, the work referred to in Chapter 4 would be continued and the influence of the strategies previously prioritised evaluated. That is, information sharing and communication between the stages of the supply chain, through means of implementing traceability systems and coordination mechanisms, could be evaluated concerning the reduction of FLW along the fruit and vegetable supply chain.

Finally, there is yet another line of investigation that must be pursued in the near future, regarding the impact of the COVID-19 outbreak on the food systems worldwide. The COVID-19 pandemic was recognised as a global issue by WHO on March 2020, while this thesis was in progress. As the COVID-19 disease spread across the world, many countries felt the need to declare a state of health emergency and to put into place a set of measures to control this spread, which included the closure of workplaces and educational institutions, and temporary restrictions in travels and social meetings. What is already know, is that the unexpected lockdowns imposed in several countries led to an exacerbated food loss and waste in the production stage, because producers were being forced to discard large amounts of fresh foods that they could no longer sell, due to the closing of restaurants, hotels and schools. Some other news also pointed to the changing of consumer habits, since the limited circulation of the population and the closing of HORECA channels led people to cook more at home and to plan their meals more consciously, leading to a reduction of food loss and waste at the household level. However, there is still no clear evidence pointing to the real impact that the current pandemic will have on the levels of food loss and waste on the long run and on its influence towards the achievement (or not) of the Sustainable Development Goals adopted by the Member States. Therefore, more in-depth investigations are needed to assess the impact of the pandemic on the provision of food around the globe and to evaluate how the change in habits will influence the levels of food loss and waste along food supply chains.

Appendix A

Table A – Detailed information regarding the 114 articles reviewed in this Chapter 2

Reference	Journal	Location of study	FSC Stage	Food Products	
				Plant-based Food	Animal-based Food
Abass et al. (2014)	Journal of Stored Products Research	Tanzania	N/S	Maize	N/S
Abualtaher and Bar (2020)	Systems	Norway	Processing	N/S	Salmon
Alexander et al. (2017)	Agricultural Systems	N/S	N/S	Crops	Livestock
An and Ouyang (2019)	Transportation Research Part E: Logistics and Transportation Review	Illinois and Brazil	Farmer, processor and exporter	Grain	N/S
Antunes et al. (2007)	WSEAS Transactions on Environment and Development	Portugal	Post-harvest handling and storage, processing and packaging, and distribution	Variety of products	N/S
Arivazhagan et al. (2016)	International Food Research Journal	India	Farm gate, traders, cold storage, processing and retailing	Fruit	N/S
Balaji and Arshinder (2016)	Resources, Conservation and Recycling	India	N/S	Fruit and vegetables	N/S
Beausang et al. (2017)	Resources, Conservation and Recycling	Scotland	Primary production	Fruit and vegetables	N/S
Bernstad et al. (2017)	Waste Management and Research	N/S	Agriculture, postharvest and storage, processing, distribution and consumption	Tomato	N/S
Bertolini et al. (2013a)	International Journal of RF Technologies: Research and Applications	Italy	Distribution	Variety of products	Variety of products
Bertolini et al. (2013b)	International Journal of RF Technologies: Research and Applications	Italy	Distribution	Variety of products	Variety of products
Bhattacharya et al. (2021)	Journal of Cleaner Production	N/S	Agriculture, manufacturing/processing, storage, logistics, retail, food service and household	N/S	N/S

Reference	Journal	Location of study	FSC Stage	Food Products	
				Plant-based Food	Animal-based Food
Bilska et al. (2018)	Sustainability	Poland	Retail	Fruits and vegetables	Meat and fish
Brancoli et al. (2019)	Resources, Conservation & Recycling	Sweden	Retail	Bread	N/S
Bräutigam et al. (2014)	Waste Management and Research	EU-27	Agricultural production, postharvest handling and storage, processing and packaging, distribution and consumption	Variety of products	Variety of products
Buisman et al. (2019)	International Journal of Production Economics	N/S	Retail	N/S	Meat
Bustos and Moors (2018)	Journal of Cleaner Production	The Netherlands, Colombia and Mexico	Importer, production/exporter, growers' associations, governmental organizations, packer and knowledge institutions	Avocado	N/S
Buzby and Hyman (2012)	Journal of Consumer Affairs	USA	Farm, processing and retail, and consumption	Variety of products	Variety of products
Buzby et al. (2015)	Agriculture	USA	Retail	Fruits and vegetables	N/S
Caixeta-Filho and Péra (2018)	International Journal of Logistics Economics and Globalisation	Brazil	Transport	Grains	N/S
Calvo-Porral et al. (2017)	Journal of Food Products Marketing	Developed countries	Agriculture and fishing, industry and processing, and retail	N/S	N/S
Chauhan (2020)	Sustainability	India	Production to retail	Variety of products	Variety of products
Chen and Chen (2018)	Sustainability	USA	Production, manufacturing, retail	N/S	N/S
Christensen et al. (2021)	Journal of Cleaner Production	Denmark	Retail and wholesale	N/S	Meat
Cicatiello et al. (2016)	Journal of Retailing and Consumer Services	Italy	Retail	Variety of products	Variety of products

Reference	Journal	Location of study	FSC Stage	Food Products	
				Plant-based Food	Animal-based Food
Cicatiello et al. (2017)	Resources, Conservation and Recycling	Italy	Retail	Variety of products	Variety of products
Cicatiello et al. (2020)	Sustainability	Italy	Retail	Variety of products	Variety of products
Corrado et al. (2017)	Journal of Cleaner Production	N/S	Primary production, transport and storage, food processing, distribution and consumption.	Fruits and vegetables	Meat, dairy, eggs and fish
de Hooge et al. (2018)	Journal of Cleaner Production	Germany and the Netherlands	Primary producers, producer organizations, and retailers	Fruits and vegetables	N/S
de Moraes et al. (2020)	Journal of Cleaner Production	N/S	Retail	N/S	N/S
De Oliveira et al. (2021)	Journal of Cleaner Production	N/S	N/S	N/S	N/S
de Steur et al. (2016)	Waste Management	N/S	Primary production, processing, storage, food service/consumption	Variety of products	Variety of products
Dora et al. (2020)	Annals of Operations Research	Belgium	Processing	Variety of products	Variety of products
Dora et al. (2021)	Industrial Marketing Management	Developed and less developed countries	On farm, manufacturing, distribution and retail or wholesale, hospitality/service industry, consumption	N/S	N/S
dos Santos et al. (2020)	Waste Management	Brazil	Supply centre	Fruits and vegetables	N/S
El Bilali and Hassen (2020)	Foods	Gulf Cooperation Council countries	N/S	N/S	N/S
Emana et al. (2017)	Agriculture and Food Security	Ethiopia	N/S	Tomato	N/S
Eriksson et al. (2014)	Resources, Conservation and Recycling	Sweden	Retail	N/S	Meat and dairy

Reference	Journal	Location of study	FSC Stage	Food Products	
				Plant-based Food	Animal-based Food
Fernandez-Zamudio et al. (2020)	Agriculture	Spain	Primary production	Persim mon	N/S
Francis et al. (2008)	Supply Chain Management	UK	Producer, processor, importer, distribution centre and food service	N/S	Beef
Gadde and Amani (2016)	British Food Journal	N/S	N/S	N/S	N/S
Gardas et al. (2017)	Renewable and Sustainable Energy Reviews	India	Harvesting, storage, processing, packaging, sales, consumption	Fruit and vegetabl es	N/S
Garrone et al. (2014)	Food Policy	Italy	Agriculture and fishing, manufacturing, retail and food service	Variety of products	Variety of products
Gautam et al. (2017)	Computers and Industrial Engineering	New Zealand	Grower, pack-house, cool-store and exporter	Kiwifrui t	N/S
Gillman et al. (2019)	Resources, Conservation & Recycling	Californi a	Agricultural production	Leafy greens, tomatoe s, and peaches	N/S
Giuseppe et al. (2014)	Waste Management	Italy	Retail	N/S	Livestoc k
Göbel et al. (2015)	Sustainability (Switzerland)	Germany	Agriculture, processing, wholesale, retail, consumption	Vegetab les and bread	Milk, dairy, meat and sausages
Gokarn and Kuthambal ayan (2017)	Journal of Cleaner Production	India	N/S	Agri-food	N/S
Gustavsson and Stage (2011)	Resources, Conservation and Recycling	Sweden	Retail	Fruits and vegetabl es	N/S
Haass et al. (2015)	International Journal of Production Economics	Europe	Distribution	Banana	N/S
Hodges et al. (2011)	Journal of Agricultural Science	USA, UK and sub-Saharan Africa	N/S	Variety of products	Variety of products
Horós and Ruppenthal (2021)	Sustainability	Germany	Retail	Variety of products	Variety of products

Reference	Journal	Location of study	FSC Stage	Food Products	
				Plant-based Food	Animal-based Food
Irani and Sharif (2016)	Journal of Enterprise Information Management	N/S	N/S	N/S	N/S
Jaja et al. (2018)	Acta Tropica	South Africa	Slaughterhouse	N/S	Livestoc k
Jedermann et al. (2014)	Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences	N/S	Distribution	Berries and bananas	Meat
Jeswani et al. (2021)	Sustainable Production and Consumption	UK	Primary production, processing and manufacturing, distribution and consumption	Cereals, fruits and vegetabl es	Meat and fish, dairy and eggs
Joensuu et al. (2020)	Waste And Biomass Management & Valorization	Finland	Primary production	Fruits and vegetabl es	N/S
Johnson et al. (2019)	Agricultural Systems	North Carolina	Primary production	Vegetab les	N/S
Kaipia et al. (2013)	International Journal of Physical Distribution and Logistics Management	Nordic countries	Grower, logistics provider, wholesaler, retailer	N/S	Milk, fresh fish, and fresh poultry
Kazancogl u et al. (2018)	Resources, Conservation & Recycling	Turkey	Agricultural production and post-harvest handling and storage	N/S	Milk
Koester (2014)	Intereconomics	N/S	Farm, wholesale and stock keeper, retail, household and restaurants	N/S	N/S
Kolawole et al. (2021)	Industrial Marketing Management	Nigeria	Processing and distribution	Biscuits and bread	N/S
Kouwenho ven et al. (2012)	International Food and Agribusiness Management Review	India and the Netherlan ds	N/S	Vegetab les	Dairy
Kuyu et al. (2019)	Heliyon	Ethiopia	Harvest, transport and retail	Potato	N/S
Liljestrand (2017)	International Journal of Physical Distribution and Logistics Management	Sweden	Industrial production, wholesale and retail	Fruit and vegetabl es	Meat

Reference	Journal	Location of study	FSC Stage	Food Products	
				Plant-based Food	Animal-based Food
Lipinska et al. (2019)	Sustainability	Poland	Transport	N/S	Dairy
Liu et al. (2016)	Journal of Cleaner Production	Japan	Production, storage and transportation, commercialization, household consumption and end of life management	N/S	N/S
Luo et al. (2021)	Sustainability	N/S	Production, Post-harvest handling and storage, processing, distribution and market, consumption	N/S	N/S
Macheka et al. (2013)	International Journal of Postharvest Technology and Innovation	Zimbabwe	Primary production, harvesting, transportation from field, grading and sorting, packing, stacking and transportation to market	Banana	N/S
Magalhães et al. (2020)	The International Journal of Logistics Management	Brazil	Production to retail	N/S	Beef
Magalhães et al. (2021)	Journal of Cleaner Production	Portugal	Production to retail	Fruits and vegetables	N/S
Marsh et al. (2001)	Journal of International Food and Agribusiness Marketing	N/S	Transport	Variety of products	Variety of products
Martínez et al. (2014)	Agronomia Colombiana	N/S	Growing and harvesting, postharvest, processing, sale and consumption	N/S	N/S
Mejjaouli and Babiceanu (2015)	Journal of Manufacturing Systems	N/S	Transport	N/S	N/S
Mena et al. (2011)	Resources, Conservation and Recycling	UK and Spain	Production, distribution and consumption	Variety of products	Variety of products
Mena et al. (2014)	International Journal of Production Economics	UK	Suppliers, retailers, wholesalers and growers/abattoirs	Fruit and vegetables	Meat
Mendonça et al. (2019)	Animal Science Journal	Brazil	Farm, transport, and slaughterhouse handling	N/S	Cattle

Reference	Journal	Location of study	FSC Stage	Food Products	
				Plant-based Food	Animal-based Food
Mercier et al. (2017)	Comprehensive Reviews in Food Science and Food Safety	N/S	Transport, storage and retail	N/S	N/S
Messner et al. (2021)	Journal of Cleaner Production	Australia	Production to retail	Variety of products	N/S
Miranda-de la Lama et al. (2014)	Meat Science	N/S	Farm, logistic stopover, slaughter,	N/S	Livestock
Munesue et al. (2015)	Environmental Economics and Policy Studies	Developed countries	Postharvest handling and storage, processing and packaging, distribution, and consumption	Variety of products	Variety of products
Muth et al. (2019)	Science of the Total Environment	USA	N/S	N/S	N/S
Newsome et al. (2014)	Comprehensive Reviews in Food Science and Food Safety	USA	N/S	N/S	N/S
Nielsen et al. (2011)	Animal	N/S	Transport	N/S	Cattle, sheep, horses, pigs and poultry
Nourbakhsh et al. (2016)	Biosystems Engineering	Illinois	Transport	Grain	N/S
Papargyropoulou et al. (2014)	Journal of Cleaner Production	N/S	From harvesting to end of life	N/S	N/S
Parfitt et al. (2010)	Philosophical Transactions of the Royal Society B - Biological Sciences	N/S	From harvesting to end of life	Variety of products	Variety of products
Parmar et al. (2017)	NJAS - Wageningen Journal of Life Sciences	Ethiopia	Agricultural production, post-harvest handling and distribution	Sweet potato	N/S
Plazzotta et al. (2017)	Trends in Food Science & Technology	N/S	N/S	Fresh-cut salad	N/S
Porat et al. (2018)	Postharvest Biology and Technology	UK and USA	Retail and consumption	Fruits and vegetables	N/S
Porter et al. (2018)	Journal of Cleaner Production	Europe and UK	N/S	Fruits and vegetables	N/S

Reference	Journal	Location of study	FSC Stage	Food Products	
				Plant-based Food	Animal-based Food
Priefer et al. (2016)	Resources, Conservation and Recycling	Europe	Agriculture, postharvest handling and storage, processing and packaging, distribution and consumption	Variety of products	Variety of products
Principato et al. (2019)	Resources, Conservation & Recycling	Italy	Cultivation, milling, production, distribution and consumption	Pasta	N/S
Prusky (2011)	Food Security	N/S	N/S	Fruits and vegetabl es	N/S
Raut et al. (2018)	Computers and Electronics in Agriculture	India	N/S	Fruits and vegetabl es	N/S
Richter and Bokelmann (2016)	Waste Management	Germany	N/S	Variety of products	Variety of products
Rossaint and Kreyensch midt (2015)	Proceedings of Institution of Civil Engineers: Waste and Resource Management	Germany	Production, wholesale and retail	N/S	Poultry
Salihoglu et al. (2018)	Bioresource Technology	Turkey	Production, post-harvest handling and storage, commercialization, consumption and end of life	Variety of products	Variety of products
Samuel et al. (2011)	African Journal of Agricultural Research	Nigeria	N/S	Maize	N/S
Schneider et al. (2019)	Waste Management	Austria and Germany	N/S	Potato	N/S
Shafiee-Jood and Cai (2016)	Environmental Science & Technology	N/S	Production, handling and storage, processing, distribution and consumption	N/S	N/S
Sibomana et al. (2016)	Agriculture and Food Security	Sub-Saharan Africa	N/S	Tomato	N/S
Silapeux et al. (2021)	Agriculture	Cameroo n	Retail	Fresh fruits	N/S
Spang et al. (2019)	Annual Review of Environment and Resources	N/S	Primary production, postharvest, retail, food service and households	Variety of products	Variety of products

Reference	Journal	Location of study	FSC Stage	Food Products	
				Plant-based Food	Animal-based Food
Taylor (2005)	International Journal of Physical Distribution and Logistics Management	UK	Farmer, processor and retailer	N/S	Fresh pork
Tesfay and Teferi (2017)	Agriculture and Food Security	Ethiopia	N/S	N/S	Fish
Thyberg and Tonjes (2016)	Resources, Conservation & Recycling	USA	N/S	N/S	N/S
Tostivint et al. (2017)	Journal of Cleaner Production	Pakistan	Farms, collection points, processing, distribution and retail	N/S	Dairy
van Giesen and de Hooge (2019)	Food Quality and Preference	N/S	Retail	Apples and carrots	N/S
Verghese et al. (2015)	Packaging Technology and Science	Australia	Agricultural production, post-harvest handling and storage, processing and packaging, distribution, food service and household	N/S	N/S
Vilariño et al. (2017)	Frontiers in Environmental Science	N/S	N/S	N/S	N/S
Wang et al. (2010)	Journal of Food Engineering	China	Transportation	N/S	N/S
Wohner et al. (2019)	Sustainability	N/S	Post-harvest handling and storage, processing and packaging, distribution and consumption	N/S	N/S
Wunderlich and Martinez (2018)	International Soil and Water Conservation Research	N/S	Production, handling and storage, processing and packaging, distribution and marketing, and consumption	N/S	N/S

Appendix B

Detailed information regarding the mitigation strategies identified in the literature and the intermediary calculation of the Fuzzy WASPAS method from Chapter 5.

Table B1 – List of mitigation strategies collected from the literature

Nr	Mitigation Strategy	Reference
1	Adjust levels of safety stock	Liljestrand (2017)
2	Adjust packaging size	Richter and Bokelmann (2016); Chen and Chen (2018)
3	Clear promotional planning process	Mena et al. (2011)
4	Correct date marking to avoid confusion	Wikström et al. (2014); Verghese et al. (2015)
5	Develop and use intelligent packaging to monitor products' safety and quality	Rossaint and Kreyenschmidt (2015); Verghese et al. (2015)
6	Develop new packaging and preservation techniques to enhance product's shelf-life	Mena et al. (2011); Mercier et al. (2017)
7	Developing new or processing products likely to be wasted	Calvo-Porral et al. (2017)
8	Ensure adherence to standard procedures	Macheka et al. (2013)
9	Ensure communication among FSC stages	Kaipia et al. (2013)
10	Find new markets for overproduction or products sorted out due to industry's quality standards	Calvo-Porral et al. (2017); Plazzotta et al. (2017); Chen and Chen (2018)
11	First-in-first-out or first-expired-first-out stock rotation in store	Mena et al. (2011)
12	Implement automated demand forecasting systems	Mena et al. (2011); Liljestrand (2017)
13	Implement integrated IT systems throughout FSCs	Mena et al. (2011); Liljestrand (2017)
14	Improve cooling methods	Emana et al. (2017)
15	Improve the means of transportation	Nourbakhsh et al. (2016); Gardas et al. (2017); Lipińska et al. (2019)
16	Improve transport infrastructures	Gardas et al. (2017); Nourbakhsh et al. (2016)
17	Improve visibility along FSCs through traceability systems	Mena et al. (2011); Verghese et al. (2015)
18	Invest in more and regularly maintain storage facilities	Munesue et al. (2015); Tesfay and Teferi (2017)
19	Share and maintain information regarding the remaining shelf-life	Kaipia et al. (2013); Macheka et al. (2013); Munesue et al. (2015); Gadde and Amani (2016); Chen and Chen (2018)
20	Training staff on handling practices	Macheka et al. (2013); Munesue et al. (2015); Emana et al. (2017); Chen and Chen (2018)

Table B2 – Normalized decision making matrix

	S01			S02			S03			S04		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,8	0,9	1,0	0,8	0,9	1,0	0,7	0,8	0,9	0,8	0,9	1,0
EC2	0,7	0,8	0,9	0,8	0,9	1,0	0,7	0,8	0,9	0,8	0,9	1,0
EC3	0,7	0,8	0,9	0,8	0,9	1,0	0,7	0,8	0,9	0,7	0,8	0,9
EC4	0,8	0,9	1,0	0,7	0,8	0,9	0,6	0,7	0,8	0,7	0,8	0,9
EC5	0,8	0,9	1,0	0,7	0,8	0,9	0,8	0,9	1,0	0,8	0,9	1,0
EC6	0,8	0,9	1,0	0,8	0,9	1,0	0,8	0,9	1,0	0,8	0,9	1,0

	S05			S06			S07			S08		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,8	0,9	1,0	0,8	0,9	1,0	0,8	0,9	1,0	0,8	0,9	1,0
EC2	0,8	0,9	1,0	0,8	0,9	1,0	0,7	0,8	0,9	0,8	0,9	1,0
EC3	0,8	0,9	1,0	0,6	0,7	0,8	0,8	0,9	1,0	0,8	0,9	1,0
EC4	0,8	0,9	1,0	0,5	0,6	0,7	0,6	0,7	0,8	0,8	0,9	1,0
EC5	0,8	0,9	1,0	0,8	0,9	1,0	0,5	0,6	0,7	0,8	0,9	1,0
EC6	0,8	0,9	1,0	0,8	0,9	1,0	0,4	0,5	0,6	0,4	0,5	0,6

	S09			S10			S11			S12		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,7	0,8	0,9	0,5	0,6	0,7	0,8	0,9	1,0	0,8	0,9	1,0
EC2	0,6	0,7	0,8	0,5	0,6	0,7	0,7	0,8	0,9	0,7	0,8	0,9
EC3	0,6	0,7	0,8	0,6	0,7	0,8	0,8	0,9	1,0	0,7	0,8	0,9
EC4	0,7	0,8	0,9	0,7	0,8	0,9	0,6	0,7	0,8	0,8	0,9	1,0
EC5	0,8	0,9	1,0	0,6	0,7	0,8	0,6	0,7	0,8	0,6	0,7	0,8
EC6	0,2	0,3	0,4	0,4	0,5	0,6	0,4	0,5	0,6	0,1	0,2	0,3

	S13			S14			S15			S16		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,8	0,9	1,0	0,7	0,8	0,9	0,7	0,8	0,9	0,6	0,7	0,8
EC2	0,7	0,8	0,9	0,7	0,8	0,9	0,6	0,7	0,8	0,6	0,7	0,8
EC3	0,7	0,8	0,9	0,7	0,8	0,9	0,3	0,4	0,5	0,4	0,5	0,6
EC4	0,7	0,8	0,9	0,5	0,6	0,7	0,4	0,5	0,6	0,5	0,6	0,7
EC5	0,3	0,4	0,5	0,6	0,7	0,8	0,6	0,7	0,8	0,6	0,7	0,8
EC6	0,7	0,8	0,9	0,5	0,6	0,7	0,7	0,8	0,9	0,2	0,3	0,4

Table B3 – Weighted normalized decision making matrix for the Weighted Sum Model

	S01			S02			S03			S04		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,39	0,44	0,48	0,39	0,44	0,48	0,34	0,39	0,44	0,39	0,44	0,48
EC2	0,17	0,20	0,22	0,20	0,22	0,25	0,17	0,20	0,22	0,20	0,22	0,25
EC3	0,09	0,11	0,12	0,11	0,12	0,13	0,09	0,11	0,12	0,09	0,11	0,12
EC4	0,06	0,07	0,07	0,05	0,06	0,07	0,04	0,05	0,06	0,05	0,06	0,07
EC5	0,04	0,04	0,04	0,03	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04
EC6	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
$\tilde{Q}$	0,77	0,87	0,97	0,79	0,89	0,99	0,70	0,80	0,90	0,78	0,88	0,98

	S05			S06			S07			S08		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,39	0,44	0,48	0,39	0,44	0,48	0,39	0,44	0,48	0,39	0,44	0,48
EC2	0,20	0,22	0,25	0,20	0,22	0,25	0,17	0,20	0,22	0,20	0,22	0,25
EC3	0,11	0,12	0,13	0,08	0,09	0,11	0,11	0,12	0,13	0,11	0,12	0,13
EC4	0,06	0,07	0,07	0,04	0,04	0,05	0,04	0,05	0,06	0,06	0,07	0,07
EC5	0,04	0,04	0,04	0,04	0,04	0,04	0,02	0,03	0,03	0,04	0,04	0,04
EC6	0,02	0,02	0,02	0,02	0,02	0,02	0,01	0,01	0,01	0,01	0,01	0,01
$\tilde{Q}$	0,80	0,90	1,00	0,76	0,86	0,96	0,74	0,84	0,94	0,79	0,89	0,99

	S09			S10			S11			S12		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,34	0,39	0,44	0,24	0,29	0,34	0,39	0,44	0,48	0,39	0,44	0,48
EC2	0,15	0,17	0,20	0,12	0,15	0,17	0,17	0,20	0,22	0,17	0,20	0,22
EC3	0,08	0,09	0,11	0,08	0,09	0,11	0,11	0,12	0,13	0,09	0,11	0,12
EC4	0,05	0,06	0,07	0,05	0,06	0,07	0,04	0,05	0,06	0,06	0,07	0,07
EC5	0,04	0,04	0,04	0,03	0,03	0,04	0,03	0,03	0,04	0,03	0,03	0,04
EC6	0,00	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,00	0,00	0,01
$\tilde{Q}$	0,66	0,76	0,86	0,53	0,63	0,73	0,75	0,85	0,95	0,74	0,84	0,94

	S13			S14			S15			S16		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,39	0,44	0,48	0,34	0,39	0,44	0,34	0,39	0,44	0,29	0,34	0,39
EC2	0,17	0,20	0,22	0,17	0,20	0,22	0,15	0,17	0,20	0,15	0,17	0,20
EC3	0,09	0,11	0,12	0,09	0,11	0,12	0,04	0,05	0,07	0,05	0,06	0,08
EC4	0,05	0,06	0,07	0,04	0,04	0,05	0,03	0,03	0,04	0,04	0,04	0,05
EC5	0,01	0,02	0,02	0,03	0,03	0,04	0,03	0,03	0,04	0,03	0,03	0,04
EC6	0,02	0,02	0,02	0,01	0,01	0,02	0,02	0,02	0,02	0,00	0,01	0,01
$\tilde{Q}$	0,73	0,83	0,93	0,68	0,78	0,88	0,60	0,70	0,80	0,56	0,65	0,76

Table B4 – Weighted normalized decision making matrix for the Weighted Product Model.

	S01			S02			S03			S04		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,90	0,95	1,00	0,90	0,95	1,00	0,84	0,90	0,95	0,90	0,95	1,00
EC2	0,92	0,95	0,97	0,95	0,97	1,00	0,92	0,95	0,97	0,95	0,97	1,00
EC3	0,95	0,97	0,99	0,97	0,99	1,00	0,95	0,97	0,99	0,95	0,97	0,99
EC4	0,98	0,99	1,00	0,97	0,98	0,99	0,96	0,97	0,98	0,97	0,98	0,99
EC5	0,99	1,00	1,00	0,98	0,99	1,00	0,99	1,00	1,00	0,99	1,00	1,00
EC6	0,99	1,00	1,00	0,99	1,00	1,00	0,99	1,00	1,00	0,99	1,00	1,00
$\tilde{P}$	0,76	0,86	0,96	0,79	0,89	0,99	0,70	0,80	0,90	0,78	0,88	0,98

	S05			S06			S07			S08		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,90	0,95	1,00	0,90	0,95	1,00	0,90	0,95	1,00	0,90	0,95	1,00
EC2	0,95	0,97	1,00	0,95	0,97	1,00	0,92	0,95	0,97	0,95	0,97	1,00
EC3	0,97	0,99	1,00	0,93	0,95	0,97	0,97	0,99	1,00	0,97	0,99	1,00
EC4	0,98	0,99	1,00	0,95	0,96	0,97	0,96	0,97	0,98	0,98	0,99	1,00
EC5	0,99	1,00	1,00	0,99	1,00	1,00	0,97	0,98	0,98	0,99	1,00	1,00
EC6	0,99	1,00	1,00	0,99	1,00	1,00	0,98	0,98	0,99	0,98	0,98	0,99
$\tilde{P}$	0,80	0,90	1,00	0,74	0,84	0,95	0,73	0,83	0,93	0,79	0,89	0,99

	S09			S10			S11			S12		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,84	0,90	0,95	0,71	0,78	0,84	0,90	0,95	1,00	0,90	0,95	1,00
EC2	0,88	0,92	0,95	0,84	0,88	0,92	0,92	0,95	0,97	0,92	0,95	0,97
EC3	0,93	0,95	0,97	0,93	0,95	0,97	0,97	0,99	1,00	0,95	0,97	0,99
EC4	0,97	0,98	0,99	0,97	0,98	0,99	0,96	0,97	0,98	0,98	0,99	1,00
EC5	0,99	1,00	1,00	0,98	0,98	0,99	0,98	0,98	0,99	0,98	0,98	0,99
EC6	0,96	0,97	0,98	0,98	0,98	0,99	0,98	0,98	0,99	0,95	0,96	0,97
$\tilde{P}$	0,64	0,75	0,85	0,52	0,62	0,73	0,74	0,83	0,94	0,71	0,82	0,92

	S13			S14			S15			S16		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
EC1	0,90	0,95	1,00	0,84	0,90	0,95	0,84	0,90	0,95	0,78	0,84	0,90
EC2	0,92	0,95	0,97	0,92	0,95	0,97	0,88	0,92	0,95	0,88	0,92	0,95
EC3	0,95	0,97	0,99	0,95	0,97	0,99	0,85	0,89	0,91	0,89	0,90	0,93
EC4	0,97	0,98	0,99	0,95	0,96	0,97	0,94	0,94	0,96	0,95	0,96	0,97
EC5	0,95	0,96	0,97	0,98	0,98	0,99	0,98	0,98	0,99	0,98	0,98	0,99
EC6	0,99	0,99	1,00	0,98	0,99	0,99	0,99	0,99	1,00	0,96	0,97	0,98
$\tilde{P}$	0,72	0,82	0,92	0,67	0,77	0,87	0,57	0,67	0,78	0,55	0,63	0,75