sustainability

MDPI

Review

Analysis of the Food Loss and Waste Valorisation of Animal By-Products from the Retail Sector

João Pinto [1], Rui Boavida-Dias [2,*], Henrique A. Matos [3] and João Azevedo [4]

[1] Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal; joao.tavares.pinto@tecnico.ulisboa.pt
[2] Low Carbon & Resource Efficiency, R&Di, Instituto de Soldadura e Qualidade, 4415-491 Grijó, Portugal
[3] CERENA, DEQ, Instituto Superior Técnico—Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal; henrimatos@tecnico.ulisboa.pt
[4] Department of Innovation & Technology Transfer, FEUGA, Campus Universitário Plaza Miralles, Local A2, 36310 Vigo, Spain; jfdomingues@feuga.es
* Correspondence: radias@isq.pt

Abstract: The meat industry generates a large amount of animal by-products not only derived from the slaughter process but also due to the losses and waste of meat products along the supply chain, contributing to the world's food loss and waste problem. Yearly, 1.7 Mt of meat in the European retail sector and 20% of meat for consumption is wasted in this sector of the supply chain. Therefore, the aim of this paper was to find and evaluate alternatives for the valorisation of agri-food residues, more specifically the meat waste from the food retail sector, through a technological perspective. Thus, we delve into the industrial processes already implemented and the emerging procedures that use muscle, bones and fats by-products from poultry, cattle and pork as the main raw materials in order to identify and characterise them. The results indicate that in addition to the current destinations—landfill, incineration and the rendering process—these animal by-products can be incorporated in the production of biodiesel, food formulations, pharmaceuticals, fertilisers and biogas through an industrial symbiosis approach. Consequently, the several valorisation processes and procedures identified not only suggest an increase in concern about the impacts of the disposal of these materials, but also highlight the potential associated with the use of animal by-products as raw material to obtain added-value products.

Keywords: agri-food business; animal by-products; food retail sector; industrial symbiosis; circular economy

check for updates

Citation: Pinto, J.; Boavida-Dias, R.; Matos, H.A.; Azevedo, J. Analysis of the Food Loss and Waste Valorisation of Animal By-Products from the Retail Sector. *Sustainability* **2022**, *14*, 2830. https://doi.org/10.3390/su14052830

Academic Editors: Helena Carvalho, Michael Martin and Radu Godina

Received: 31 December 2021
Accepted: 24 February 2022
Published: 28 February 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Nowadays, there is a greater concern with the responsible management of available resources and the reduction of the environmental impacts caused by the production of solid waste and liquid and gaseous effluents. According to the Food and Agriculture Organization of the United Nations (FAO) [1], every year, approximately one-third of the world's food is lost or wasted, to which the major contributions are from developed countries, where more than 40% of the wastage occurs in the retail sector and at the consumer level. Allied to this, the wastage associated with the final stages of the food supply chain—retail sector and household—are the ones with the highest environmental impacts and economic costs since they imply the accumulation of all the resources, energy and emissions associated not only with the stage itself but also with the ones that preceded it [2]. As a result, it becomes increasingly important not only to reduce food waste, but also to find alternatives for using and transforming the waste generated in the agri-food business into added-value products so as to make better use of resources and make the food supply chain (FSC) more sustainable and circular.

The meat industry is one of the industries in the agri-food business with the greatest environmental impact. Meat is the most valuable livestock product, and world consumption has increased 18% between 2008 and 2018 due to declining prices coupled with nutritional trends [3,4]. However, the increase in the consumption of meat leads to an increase in the production of residues, which are either sent to the rendering process, incinerated or put in a landfill [5]. In addition, meat products are perishable, and globally, 20% of the meat produced is wasted, contributing to the world's food waste problem [6]. Overall, the meat industry is responsible for 14.5% of the anthropogenic emissions of greenhouse gases (GHG) [7]. In the European Union (EU), 14 million tonnes of meat are lost and wasted annually, of which 76% are wasted in the final steps of the food supply chain [8], resulting in the generation of waste in the form of animal by-products (ABPs) such as muscle, bones and fats.

The growing concern for better management and use of resources and the reduction of waste leads to the need to find processes that make it possible to obtain added-value products from this waste. To ensure this, industrial symbiosis (IS) is a solution that promotes the synergistic exchange of resources, including water, energy, waste, by-products, residues and materials, creating a more sustainable industrial system [9]. According to this approach, the residues and by-products generated by a company are sent to other production processes, which increases the life cycle and efficiency of the exchanged material [10].

Current literature reviews on food waste [11–14], indicate that although there is greater research and technological development related to food waste (mainly focused on agro and biowastes), there is a gap in the study of the valorisation waste of meat products. Moreover, waste valorisation is often overlooked in favour of other strategies, such as: waste minimisation, forecasting, stock and inventory control and supply chain coordination aspects [15]. This further emphasises the need for studying animal by-product valorisation pathways. Therefore, the scope of this work is to identify and characterise the current and emerging alternatives for the valorisation of ABPs generated in retailing activities (muscle, bones and fats) in a context of value creation through IS.

This study is focused on retailing activities for two main reasons. Firstly, the importance of retailing activities to the generation of food waste has been pointed out in Bhattacharya et al. (2021) [16] due to the high volume of traded products and for having a large influence on the decision for the ultimate destination of the wastes, such as disposal, incineration, recycling or donation. Although incineration is an energy recovery process, according to the Waste Framework Directive of the European Commission [17], this is a low-priority process in the hierarchy of possible destinations for food waste, with prevention, reuse and recycling being preferable. Added to this, the landfilling or incineration of these ABPs intensifies the environmental pollution of soils, air and groundwater. Moreover, the fact that the products sold by retail have been through a processing stage and are ready for human consumption facilitates the separation of the waste, and thus these products have the most potential for being valorised and transformed into value-added products. Secondly, despite slaughterhouses making a significant contribution to food waste and loss, the type and nature of this waste (carcasses and dead animals) have very specific regulations for disposal, thus limiting its use in value-added production processes.

This research aims to achieve three main objectives: (i) contextual analysis of the food supply chain from a sustainability perspective, concerning the production of residues, its causes and impacts; (ii) identification and characterisation of the consumption and wastage in the meat industry, as well as potential by-products for valorisation; and (iii) identification and techno-chemical characterisation of the technologies for the valorisation of ABPs from the perspective of both emergent and new, promising alternatives and industrial scalarised processes.

The remainder of the paper is as follows. Section 2 describes the methodology used for the review. Section 3 provides a contextual analysis on food losses and waste in the agro-food sector, which is further explored specifically in relation to the meat sector in Section 4. Section 5 provides a review of waste valorisation pathways of animal by-products (meat, fats and bones) with respect to emergent and industrial-scaled processes. A discussion and final conclusions are presented in Section 6.

2. Methodology

For the current research, a multi-method was employed, combining desk research with snowballing and a more systematised literature review process (Figure 1).

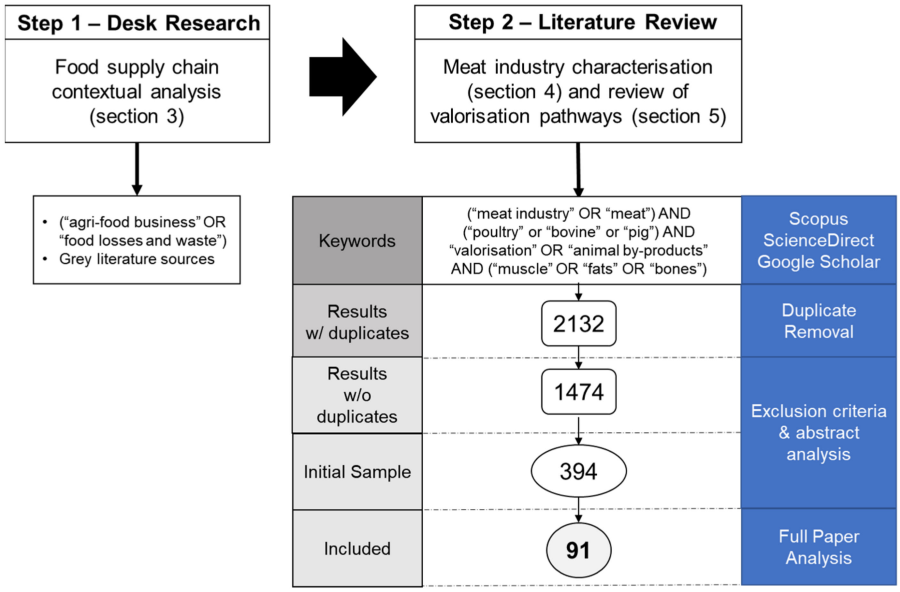

Figure 1. Research methodology.

First, a desk research method was employed to understand and identify critical problems in the agro-food sector, namely the identification of causes and impacts of food losses and waste. The research started with the use of the keyword string ("agri-food business" OR "food losses and waste") in the Google Scholar search engine. A total of 12 articles were collected, including grey literature sources, which comprised Step 1 of the research methodology, as preconised in Figure 1.

To properly address the objectives of the research, a more thorough and systematic analysis was performed. This comprised Step 2 of the literature review, concerning: (i) the consumption trends, the food waste of this industry and the composition of the animal by-products generated in the retail sector; (ii) the identification and characterisation of valorisation processes and technical procedures for using animal by-products as added-value products. For this, an electronic search was performed using three database platforms: ScienceDirect, Scopus and Google Scholar. These databases were used to find journal papers, articles and conference proceedings in English published on the topic between 2000 and 2022. The information gathered from Step 1 allowed us to combine relevant keywords related to the objectives of the research by using the "AND" operator. The combinations and explanations were as follows:

(a) ("meat industry" OR "meat") to focus the research on the meat sector.
(b) ("poultry" OR "bovine" OR "pig") to capture more precise information focused on the selected animals.
(c) ("valorisation" OR "animal by-products") AND ("muscle" OR "fats" OR "bones") to obtain specific valorisation processes for each animal by-product considered in the study.

The combination of the three research strings totalled a number of 2132 articles, which were analysed to eliminate redundancy from duplicates across the science databases. The relevant total was then considered to be 1474 articles. From this, only the articles with a well-described experimental procedure and whose results allowed a possible scale-up or implementation at an industrial scale were considered. Therefore, the application of different search terms and filters led to a total of 91 scientific articles being considered in this study. The results of the analysis are found in Sections 4 and 5 of this research. The majority of publications were published after 2009, and the oldest and the most recent articles considered were published in 2003 and 2022, respectively.

3. The Agri-Food Business

The agri-food business is comprised of interrelated activities working together to provide goods and services to consumers around the world. It comprises the link between the primary sector (agriculture and livestock production) and the industrial sector, providing the conversion of raw agricultural materials into added-value products (Figure 2) while generating employment, profit and economic development [18].

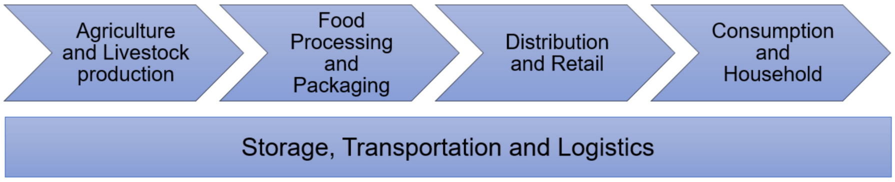

Figure 2. Food supply chain. Adapted from Ref. [19].

All the activities related to the agri-food business have a great economic, social and environmental impacts. In 2015, this USD 5 trillion (approximately EUR 4.4 trillion) business represented 10% of global consumer spending, 40% of employment and 30% of GHG emissions [20]. Concerning the European agri-food business, the meat sector is the largest sub-sector, representing 20% of the total turnover [21].

This business is in continuous development concerning safety and quality, which are identified as its biggest challenges. These challenges occur because the agri-food business deals with products for human consumption, which are directly linked to human health. Consequently, it is considered as the most regulated European activity business [22].

3.1. Food Loss and Food Waste

In the agri-food business, one of the major problems affecting all the activities and their sustainability is food loss and waste across the food supply chain (FSC). This problem is caused not only by biological and climate factors, but also by the behaviour of the FSC's actors, which are linked to socio-economic factors mostly related to strategic and operational decisions, such as the incorrect application of inventory turnover, improper conditions of storage and transportation or increasingly varied menus [23,24]. According to the FAO [1], food loss and food waste refer to the decrease in food intended for human consumption in the subsequent stages of the FSC (Figure 3).

Despite food loss and food waste seeming like interchangeable terms, each has a clear definition and, consequentially, different solutions. Food loss refers to the decrease in edible food mass throughout the part of the FSC that leads to edible food for human consumption, which means that food gets spilled or spoilt before it reaches its final product or the retail sector [25]. This problem takes place at different stages, which include production, post-harvest and processing, due to inefficiencies in supply chains [26]. Food waste refers to food that is of good quality and fit for human consumption but does not reach that goal and is discarded at the end of the food chain, which generally includes the stages of distribution, retail and consumption [26,27].

According to the FAO's 2011 report [1], food losses and waste represent one-third of all the edible food produced for human consumption, totalling 1.3 Gt per year and an economic cost of USD 990 billion (approximately EUR 728 billion). Most of the wastage occurs in developed countries, where more than 40% occurs at the retail and consumer levels. In Europe and North America, the per capita food loss is approximately 280–300 kg/year, while the per capita food waste is 95–115 kg/year. In developing countries in Africa and Asia, the per capita food loss is 120–170 kg/year, and the per capita food waste is 6–11 kg/year [1]. Table 1 shows the average percentage of wastage of different commodities [6].

Table 1. Food loss and waste (%) in different types of food products. Adapted from Ref. [6].

Food Product	Food Loss and Waste (%)
Fruits and vegetables	45
Cereals	30
Fish and seafood	35
Meat	20
Dairy products	20

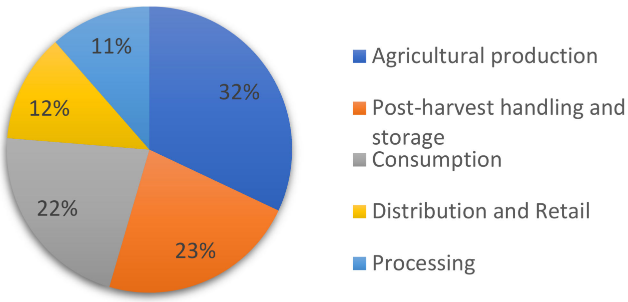

Figure 3. Share of global food loss and waste by stage of the food supply chain (100% = 1.3 billion tonnes). Adapted from Ref. [28].

Worldwide, the most wasted type of food is cereals, contributing 26% to the total amount of wasted food. However, vegetables are the major contributors to the economic losses associated with food waste, based on producer prices [28]. Concerning the distribution of the wastage, it is important to highlight the meat products, which, despite contributing only 4% to the total amount of wasted food, contribute 22% to the economic losses associated with food waste (Figure 4).

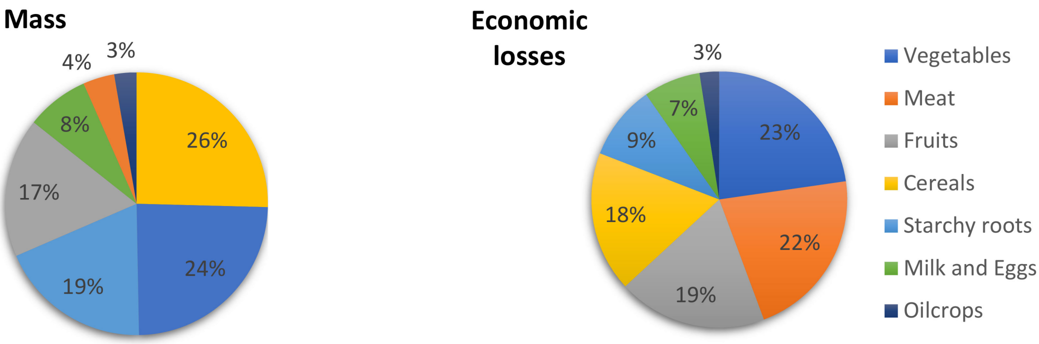

Figure 4. Contribution of each commodity to food losses and waste and distribution of the economic losses. Adapted from Ref. [28].

In the EU, every year, 88 Mt of food is lost and wasted, which represents an associated cost of EUR 143 billion. The stages with the greatest contribution are households and food processing, which together account for 72% of EU food wastage [2].

3.1.1. Causes of Food Loss and Waste

According to Katsarova (2016) [29], food loss and waste are spurred by three major global trends. The most important one is urbanisation, which has resulted in the gradual extension of the FSC, increasing the remoteness between the place of production and that of final consumption. This remoteness requires the transport of food products over greater distances and, consequently, the improvement of transport and storage to avoid additional losses. The second global trend is the change in the composition of diets. This phenomenon is mainly observed in economies in transition, such as Brazil, India and China, and involves a shift from starchy diets to ones consisting of meat, fish and fresh products such as fruits and vegetables, which perish more quickly. The third global trend is the increasing globalisation of commerce and large-scale distribution, which result in the need for higher-quality products and safety standards for consumers and an increase in the volume of products marketed [29].

However, food loss and waste are spread over all the stages of the FSC (Figure 5), and due to that, the causes of wastage will be different. The following sections describe the causes of food loss and waste for each stage of the FSC.

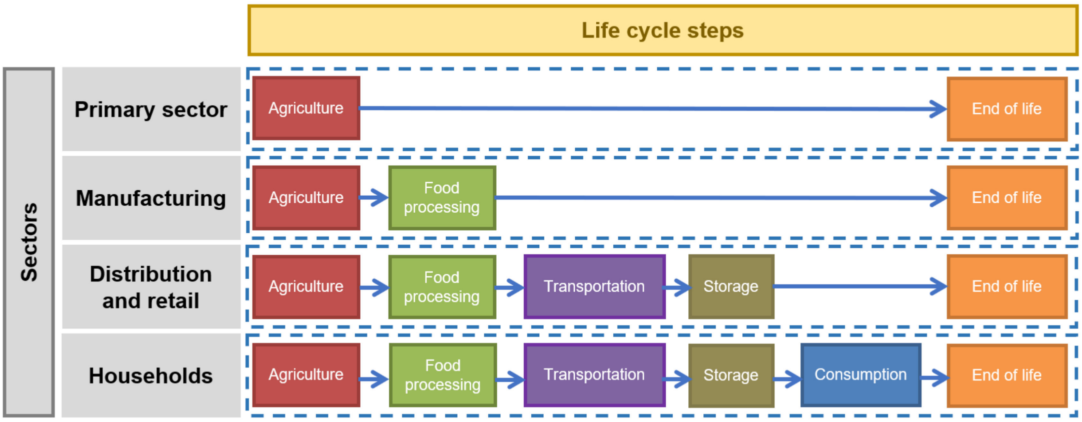

Figure 5. Food loss and waste in each stage of food supply chain. Adapted from Ref. [30].

Agriculture and Livestock Production

Agriculture and livestock production are the beginning of the FSC and are responsible for about one-third of the world's food loss and waste. The losses at the primary sector are higher in developing countries than in developed ones, and they are mainly the result of a lack of technology development in operations, such as harvesting, transport and storage, and insufficient infrastructure [31].

In developed countries, the main causes are overproduction, problems in the manufacturing process, which lead to irregularly sized products being trimmed to fit or discarded entirely, or technical malfunctions that lead to product damage [32]. Another important cause is health and safety concerns, in which improper or unsafe food, due to contamination, has to be discarded in order to prevent risks for consumers' lives and health [33]. An example of contamination is veterinary drugs (anabolic steroids and antibiotics), which, when applied to animals, can lead to serious consequences for humans, including cancers and changes in the immune system. In addition, the primary production sector is highly affected by climatic and environmental factors and can also be affected by pests, fungus and diseases which make food products unsuitable for consumption. One reported case of disease was the spongiform encephalopathy that affected cattle, which was triggered by an infectious agent (prion) and infected more than 500 thousand animals worldwide [26].

The retail sector also has an influence on agriculture and livestock production due to its high quality standards for fresh products. These standards concerning size, shape, weight, colour and appearance lead to the rejection of some products that will not be harvested, contributing to the food waste problem [34].

Food Processing and Packaging

In food processing and packaging, the main causes for food losses are over-production, technical problems during processing and quality assurance measures [35]. During food processing, power blackouts can occur occasionally due to fluctuations in the public power, which can lead to uncontrolled alterations or decay of food products, especially in operations that demand specific operating conditions, such as cooking or fermentation. Food losses during processing may also occur due to cleaning, as some product residues always remain in the equipment and will be lost during cleaning operations [35].

Quality assurance measures during the processing of food products are due to specific industry requirements, such as sizes and standards, that result in several selections during the processing steps and lead to high waste rates [1].

Retail and Distribution

Food waste can occur during distribution due to losses or damages to products as the result of improper transportation and handling, such as insufficient securing of the pallets or changes in storage temperatures, or during the loading and unloading of goods [32,36].

According to Stenmarck et al. (2016) [2], retail food waste is estimated as being 4.6 Mt in EU, which represents about 5% of the total food wasted along the supply chain. Although retail food waste is low, its study is important because retailers have great influence in shaping the features of food production and the preferences of consumers; in addition, retail stores are a place of intersection of several food chain actors [23]. Added to this, since the retail sector is one of the last stages of the FSC, the food wasted at this stage has a greater environmental and economic impact, as it accumulates the impacts and resources used in this and in previous stages [2].

Retailers are often confronted with the problem of oversupply because customers expect a wide range of products and full shelves, and this permanent availability of food products is a problem, especially with perishable products [32]. Therefore, the causes of retail food waste are the short shelf life of perishable food products; the existence of too many of each product so that they cannot be all sold before the best-before date; and turnover, which also has an influence on the percentage of waste and poor stock turnover management [37,38].

Consumption and Household

The major problem in the consumption stage that leads to food waste is portion size. In fact, according to Engström et al. (2004) [39], on average, 20% of the food in this stage is wasted, of which 50% is due to leftovers on plates. Other important factors that affect the gastronomic sector are the quality of the food produced, especially in places such as schools, workplace canteens and hospitals, and the logistical problems concerning the planning and purchasing of food products, usually related to the variation in the number of customers.

Household or private consumption is the main contributor to food waste in developed countries, and the avoidable waste is usually composed of leftovers, opened food items and sealed groceries [31,40]. Shopping is one of the main contributors to food waste at the household level because many consumers do not plan or poorly plan their shopping, which leads to spontaneous purchases and buying beyond their own needs. This type of behaviour, allied to the consumers' trends to try novel and unknown products that might not be fully enjoyed or eaten, might lead to significant amounts of waste that could be avoided. Another important reason for food waste is poor storage management, concerning not only storage conditions, such as climate and temperature, but also the control of food date labelling of food products [40]. In addition, oversized meals prepared at home coupled with a lack of skills for recombining leftovers into new meals also have an impact on the world's food waste problem [32].

3.1.2. Food Loss and Waste Impacts

The food cycle, from primary production to consumption, is one of the most resource-demanding cycles, as well as one of the most polluting, with large quantities of pollutant emissions released into the water, soil and air.

Energy consumption is spread across all stages of the FSC. Starting with agriculture and livestock production, it is the most energy-intensive stage, consuming one-third of all energy used in operations such as cultivation, animal rearing and irrigation. Food processing and packaging are responsible for 28% of the total energy used, which are distributed in several unitary operations, such as milling, cutting, mixing, drying and sterilisation. Analysing the retail and distribution stage, the transport and logistics of food products account for 9.4% of the energy used in the FSC, while the fuel and electricity needed to maintain the retail centres and local shops account for 10.7%. The consumption stage accounts for 13% of the total energy used, which is mainly associated with food product conservation, preparation and cooking, and finally, the end-of-life stage, which includes all the waste management operations, accounts for 5.5% of the total energy used [41].

Environmental Impacts

In order to quantify the impacts of this problem on the environment, the FAO assessed the carbon footprint, water footprint and land used. According to the FAO [28], the global carbon footprint of food waste is estimated at 3.3 Gt of CO_2-eq, and the main contributors are cereals (34%), meat (21%) and vegetables (21%).

Water footprint measures the volume of water required to produce a certain product and includes three forms of water use: green, blue and grey water. Green water is more relevant in agriculture, and it is the water resulting from precipitation that is stored in the soil and will be incorporated by the plants. Blue water is the surface water or groundwater, and it is also used in agriculture, industry and domestic areas. Grey water is the volume of freshwater needed to assimilate the load of pollutants based on existing ambient water quality standards [42]. The FAO assessed the total use of blue water concerning food wastage, concluding a blue water footprint of 250 km^3, of which 92% is used in the primary sector [43].

Regarding land use, the total uneaten food occupies almost 1400 million hectares, which represent about 30% of the world's total agricultural land area. Milk and meat products are the main contributors for land occupation, representing approximately 80% of the total land used by food waste products [28].

Economic Impacts

The global economic impact of food wastage implies the sum of several categories, including environmental, economic and social costs. The environmental costs represent all the costs associated with atmosphere (GHG emissions), water (water scarcity, use and pollution), soil (soil erosion and land occupation) and biodiversity. The economic costs represent the loss of economic value based on producer prices, and the social costs are all the costs associated with livelihood loss, risk of conflict and health damages (Table 2) [44].

Table 2. Costs of food wastage by category in 2012. Adapted from Ref. [44].

Category	Cost (Billion USD)
Environment	690
Economic	1050
Social	880
Total	2620

The cost of food wastage is also dependent on the stage of the supply chain. Therefore, the later the food product is lost along the chain, the greater the environmental impact will be due to increased use of resources and energy, and, consequently, the greater the cost per tonne of food wasted will be (Table 3). Concerning this, the reduction and prevention of food waste is even more important in the later stages of the FSC (retail and household).

Table 3. Cost per tonne of edible food waste by stage. Adapted from Ref. [2].

Stage	Cost (EUR/Tonne)
Agriculture and livestock production	399
Food processing and packaging	1490
Retail and distribution	2768
Consumption and household	3529

According to Table 3, the most significant variation occurs between the processing and retail stages, where there is an increase of, approximately, 1300 EUR/tonne, which gives more emphasis to the importance of reducing food waste in the later stages.

Social Impacts

The social impact of food loss and waste can be tackled using two concepts: food security and access to food. Food security refers to the availability of food products in such quantities that will satisfy the energy requirements and nutrient content of the population. According to the FAO's 2014 report [44], the social impacts of food wastage can also be divided into two components: primary impacts, which are felt directly by the individual in terms of quality of life or well-being, and secondary impacts, which are felt more widely by society, such as increases in health and medical expenses. Regarding the primary impacts, food loss and waste have a great impact on food security and nutrition. Concerning the secondary impacts, these are expressed in the form of losses in human capital and gross domestic product (GDP).

4. Consumption and Waste Analysis of the Meat Industry

Meat is the most valuable livestock product, and the meat industry includes all of the steps from the production of livestock to the distribution and marketing of meat products. Over the last several years, the consumption of these products has been increasing (Figure 6) due to several reasons, which could be economic, such as the liberalisation, declining prices and globalisation of food systems; demographic, such as urbanisation and the increase in the world's population; or due to nutritional trends [3,4]. Overall, global meat consumption registered a compound annual growth rate (CAGR) of 1.6% over the last 15 years. The most consumed fresh meat and meat products are derived mainly from poultry, cattle and pigs. Currently, poultry is the most consumed meat in the world (Figure 7) due to the lower production costs, which lead to lower retail prices than beef or pork [45], and due to greater awareness in reducing the consumption of red meat, since it is a high-fat food and potentially carcinogenic for humans [46].

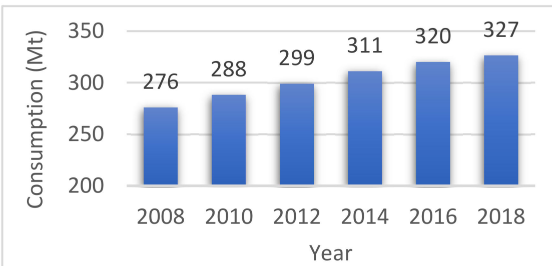

Figure 6. Evolution of world meat consumption, in millions of tonnes. Adapted from Ref. [47].

Environmental impacts stem from the scale of production and a lack of consideration for the effects of inputs (land, water and energy) and surplus outputs, such as manure and by-products, which cause air, water and land pollution and the depletion of natural resources. Consequently, the global livestock sector contributes significantly to climate change, with GHG emissions estimated at 7.1 Gt CO_2-eq per year, representing 14.5% of anthropogenic GHG emissions. Beef production accounts for the majority of GHG emissions, contributing 41% of the sector's emissions, while pork and poultry meat contribute 9 and 8%, respectively [7].

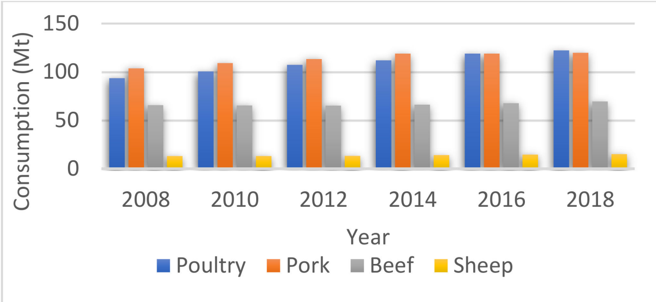

Figure 7. World meat consumption by species, in millions of tonnes. Adapted from Ref. [47].

From farm to fork, meat losses are spread across the FSC, starting with primary production, where mortality and disease are the main causes of losses, followed by slaughter and processing, due to the removal of inedible parts. Consequentially, the percentage of retail saleable meat from the carcass weight is approximately 45% for ruminants, 56% for pigs and 60% for chickens. However, in the final stages of the meat supply chain, there is still meat waste, corresponding to about 20% of the meat available in the retail sector (Figure 8) [48].

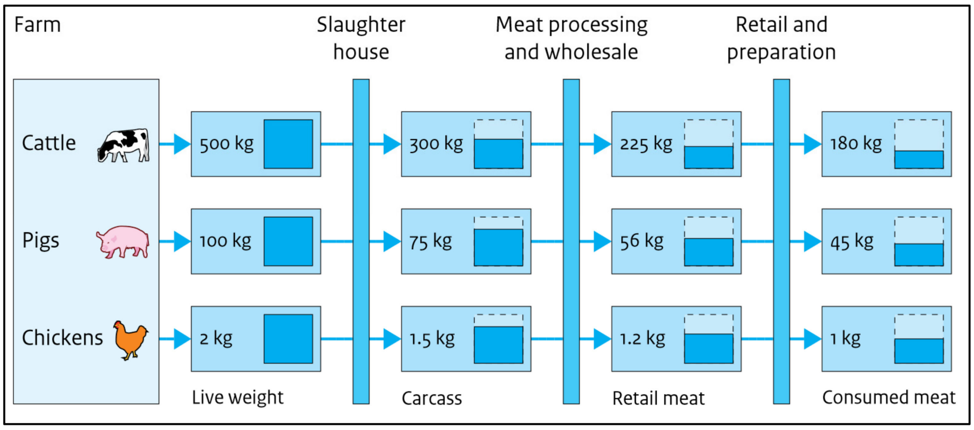

Figure 8. Overview of losses and waste in the meat chain. Adapted from Ref. [48].

In 2011, the meat lost or wasted was 23% of the total meat available for consumption in the European Union. The consumption stage was responsible for the largest share of waste (64%), followed by processing (21%) and retail sectors (12%). Table 4 and Figure 9 synthesise meat losses and waste across the European supply chain [8]. The meat available for consumption also contains some bones and fats, which represent an inedible fraction of the meat. Accordingly, in the consumption stage, the meat waste can also be divided into edible and inedible fractions. Therefore, the total amount of edible meat wasted in this stage was approximately 4.3 Mt, and the inedible fraction was 4.7 Mt [8].

Although the consumption stage is the one that has the greatest influence on the waste of meat products, the collection and management of by-products generated in this stage is difficult due to the high number of households, which leads to the dispersion of meat waste, and the small portions of meat waste generated by each consumer. In addition, these by-products are usually discarded together with household waste, which makes separation complex, compromising further processing.

Table 4. Meat losses and waste across the European supply chain in 2011. Adapted from Ref. [8].

Stage	Meat Losses and Waste (Mt)
Primary sector	0.5
Processing	2.9
Retail	1.7
Consumption	9.0
Total	14.1

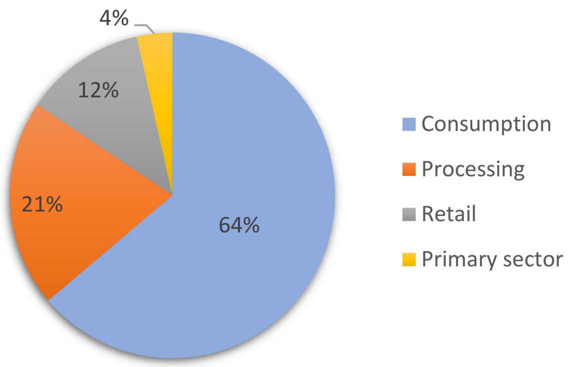

Figure 9. Share of European meat waste by stage of the supply chain. Adapted from Ref. [8].

Regarding the primary sector, the wastage is mostly related to the mortality of animals in production sites due to natural causes or diseases, which makes them more difficult to use and valorise. Accordingly, in the first instance, the attention will be focused on the waste generated in the processing and retail stages since they represent one-third of the total meat waste and because larger quantities are generated each time, which are less dispersed geographically, allowing for better management and collection.

Currently, according to Toldrá et al. (2012) [49], the disposal of such wastes remains a major problem in the meat industry. These by-products used to be sent to incinerators or landfills, which intensified environmental pollution. Nowadays, the problems associated with their disposal are due to the high associated costs in order to comply with the current legislation. In the retail sector, the main animal by-products are the muscle, bones and fats which are generated not only by the meat cutting process at the butcher, but also by the end of their expiration date.

Legal and Regulatory Framework

The legal context associated with products of animal origin has undergone several changes over time, most of them influenced by the outbreak of transmissible spongiform encephalopathy (TSE), commonly known as "mad cow disease".

In the European legislation expressed in Regulation 1069/2009, the Animal By-products Regulations [50], an ABP is defined as a full body, parts of animals or products of animal origin which are not intended for human consumption, including embryos, oocytes and semen. In the same regulation, the ABPs are divided into three categories according to the level of risk to public and animal health, which will lead to different elimination/valorisation methods. The categories are:

- Category 1—the highest-risk category that includes all the animals or parts of animals suspected or already infected with transmissible spongiform encephalopathy (TSE) and animals containing residues of other substances at a concentration above the established limits.
- Category 2—medium-risk category that includes manure and animal products declared unfit for human consumption due to the presence of strange bodies or the presence of contaminants at a concentration above the established limits.

- Category 3—low-risk category that includes carcasses or parts of animals that, in accordance with Community legislation, are fit for human consumption but, due to commercial reasons, are no longer intended for that end. This category includes heads, feet, feathers and hides.

According to the ABP Regulations, the possible elimination or valorisation methods associated with each category are synthesised in Table 5. The landfilling of some materials of categories 2 and 3 is allowed, but they must undergo a sterilisation treatment that modifies the initial meat product in order to ensure that it poses no risk to human and animal health, as described in the Regulation 142/2011 of the European Commission related with the health rules concerning ABPs [51].

Table 5. Possible elimination/valorisation methods for each animal by-product category [51].

	Incineration or Co-Incineration	Landfill *	Composting or Biogas *	Fuels	Organic Fertilisers	Animal Feed
Category 1	X			X		
Category 2	X	X	X	X	X	
Category 3	X	X	X	X	X	X

* After sterilisation treatment.

ABPs of the retail sector (muscle, fat and bones), according to the definition of the three categories, are inserted in category 3. In spite of being a low-risk category, the use of some ABPs included in this category in the feeding of some animals is still restricted by Regulation 999/2001 of the European Commission due to the possibility of TSE infection (Table 6) [52].

Table 6. Possible use of category 3 animal by-products in animal feed [52,53].

		Ruminants	Non Ruminants	Fish	Pets and Fur Animals
Ruminants	Blood				√
	Hydrolysed proteins				√
	Collagen				√
Non ruminants	Blood		√	√	√
	Hydrolysed proteins	√	√	√	√
	Collagen	√	√	√	√
Fish meal			√	√	√

5. Valorisation of Animal By-Products

The treatment and reduction of animal by-products has registered an increase in the awareness that this type of materials is underutilised and can represent a valuable resource if treated correctly. Consequently, it is no longer practical to dispose of animal by-products, especially when a significant amount of potential raw materials is produced, which can have a high economic potential through the production of new products with significant added value.

The reuse and valorisation of animal by-products (ABPs) generated in the food retail sector can involve sending these by-products to another company/organisation or industry, where they will be processed in order to obtain added-value products. This type of valorisation originates an industrial symbiosis.

5.1. Industrial Symbiosis

Industrial symbiosis (IS) is the evolution of the concept of industrial ecosystems, first proposed in 1989 [54]. Therefore, IS is the approach of a more sustainable integrated industrial system that identifies business opportunities which leverage the synergistic exchange of underutilised resources, including water, energy, material, residues, waste and by-products [9]. IS involves organisations operating in different sectors of activity, and its main objective is not only to avoid the use of landfills, but also to maximise the reuse and recovery of surplus streams, preventing resources from becoming waste as a first option.

In 2008, the definition presented by Chertow [10] suggested a criterion of distinguishing IS from other exchanges, the 3-2 heuristic. According to this heuristic, IS has to involve at least three different entities and the exchange of at least two different resources without any of the entities having recycling as the main function.

Companies producing waste can implement two distinct IS strategies: internal IS, where the company uses the waste produced by a given production process in other production processes within the company's boundaries, replacing inputs of virgin raw materials, or external IS, where a company sends their waste to other companies that will use it in their production processes [55].

The ultimate objective of IS is producing more without spending more resources or energy through cooperation between organisations, where companies use waste or by-products from other companies. This is an effective method of "locking" the matter cycle and, consequently, to obtain a zero level of waste. According to Neves et al. (2020) [56], the implementation of an IS project can have several beneficial impacts not only on an environmental level, but also on a social and economic level. The environmental benefits are mostly related to the reduction of the impacts associated with the processes and methods of waste disposal and the extraction and import of virgin raw materials, which lead to GHG emissions, scarcity of natural resources and waste that would stop at landfills and incinerators. The social benefits are due to the creation of jobs by new activities related to the transformation of residues and by-products and the valorisation of labour resources due to the decrease in costs of raw materials. Combined with social and environmental benefits, an IS project also leads to economic gains that are related to the reduction of raw material costs and waste treatment. In addition to these benefits, an IS project can also be a possible solution for organisations in order to meet environmental requirements, such as reducing GHG emissions.

These impacts verified at different levels demonstrate that creating synergies is not only about the exchange or sharing of resources; it is also a new value creation process for all parties involved. Therefore, the overall value created globally by the synergy will be greater than the sum of the value created by the organisations operating independently [57].

5.2. Implemented Industrial Processes and Technologies

Concerning the ABPs of the retail sector (muscle, bones and fats), the industrial processes and technologies already applied to this type of organic by-products were assessed. ABPs have a high content of proteins and lipids, and consequently, many possible technologies for the valorisation of these materials are related to the extraction or recovery of these components due to the possibility of developing new products from them for commercial applications. However, the application of ABPs is challenging because by-products do not have a homogeneous composition, have low water solubility and also have a high risk of being contaminated with pathogens, which leads to the need for special operating conditions [58].

On an industrial scale, the most used process in the management of all ABPs is the rendering process, in which the stabilisation and sterilisation of these materials occur by digesting them under severe conditions of temperature and pressure (133 °C, 3 bar, 20 min). The sterilisation step consists of removing hazardous microorganisms, eliminating the risk of diseases, while the stabilisation step involves water removal to prevent product decomposition, making its storage safer for later use in other production processes. Its two main final products are animal meal and animal fat, which can be used as animal feed and for biodiesel production, respectively. This process includes an initial step of reducing the granulometry of the meat products (up to approximately 50 mm), followed by a heat treatment for sterilisation in a continuous or discontinuous system under the conditions of pressure and temperature mentioned above. After the digestion step, the product obtained is pressed in a screw press to separate the solid fraction from the liquid fraction. The solid stream is fed to another screw press, operating at higher pressure, to remove the residual water and fat. The main output of this screw press is a solid stream, rich in protein, that will be dried and ground, originating a solid product: animal by-product meal. The liquid stream obtained in the first screw press is decanted to remove entrained solid particles, and it is centrifuged to separate the organic phase from the aqueous phase. After this step, the products obtained are an aqueous stream, which will be treated before being discharged into the environment, and an organic stream, animal fat, that is stored. The water removal is very important in the rendering process, and the aqueous stream obtained represents about 65% of the initial mass of the raw materials [59,60].

The BioRefinex process also incorporates all ABPs generated in the retail sector, where the combination of thermal hydrolysis and anaerobic digestion allows for the production of organic fertilisers and biogas with a methane content between 55 and 75% [61].

Regarding bones, pyrolysis technology can be used for the production of charcoal, which in turn can be applied as an organic fertiliser due to its high concentration of phosphorus and calcium and low carbon content that give the charcoal great agronomic efficiency. This final solid product obtained is called bio-phosphate [62]. The application of this technology to animal bones reduces the use and exploitation of mineral phosphate (apatite), which is a compound widely used in the formulation of agricultural fertilisers, and according to European Commission (2017) [63], it is classified as a critical raw material due to its economic importance and high supply risk. In pyrolysis, the bones are crushed and sent to a pre-treatment of sterilisation, similar to the rendering process, whose operating conditions are 133 °C, 3 bar and residence time of 20 min. The solid stream obtained is fed to the 3R pyrolysis reactor (recycle–reduce–reuse), where the pyrolysis occurs at 850 °C at a relative pressure of −50 Pa for 20 min. During pyrolysis, the volatile substances and proteins are removed from the mineral part, and the products obtained are a solid stream (bio-char) and a gas stream. The effluent gas stream from the pyrolysis reactor is sent to cyclones in order to remove some solid particles that have been entrained with the gas. Then, it goes to a partial condenser, in which a part of the gaseous stream is condensed, obtaining a liquid stream composed of an aqueous and an organic phase. The non-condensed gases (pyrolysis gas) are sent to storage and can be used as syngas or can be directed to catalytic processes for the production of jet fuel or nitrogen recovery. The liquid stream obtained after the partial condensation of the gases is centrifuged or decanted to separate the existing phases, obtaining an aqueous phase and an organic phase (bio-oil), which can be used as a fuel. After drying, the final solid product obtained represents 46% of the initial mass of raw materials [60].

The gelatine production process uses the combination of an alkaline pre-treatment and thermal hydrolysis to produce gelatine from animal bones, usually from cattle. In this process, the bone particles are subjected to demineralisation by adding a hydrochloric acid solution for the removal of the inorganic content. Then, the alkaline pre-treatment with a supersaturated lime solution allows non-protein substances to dissolve and changes the structure of collagen, making it soluble in water. Finally, the thermal hydrolysis involves about 3–6 extractions in series at progressively higher temperatures, with 5–10 °C difference between steps. The first extraction takes place at a temperature of 50–60 °C, and the last usually takes place at a temperature close to the boiling point of water (100 °C). This procedural step involves the breakdown and solubilisation of collagen. After concentration of the solution of hydrolysed collagen, the gelatine obtained has a water content of 10% and less than 1% of impurities [64,65].

Animal bones can also be used in the production of chondroitin sulphate, which is one of the acids that make up the intercellular substance, responsible for repairingcells and giving firmness totissues. This industrial process uses the combination of enzymatic and alkaline hydrolysis to obtain a chondroitin sulphate powder with a degree of purity greater than 90% [66]. The final product has many applications, namely in the pharmaceutical industry, such as the production of medicines for osteoporosis problems, in the cosmetics industry, for the production of creams and products for hair and skin, and in the animal feed industry, where it can be used as a food supplement.

Muscle has thermal and enzymatic hydrolysis as its main destinations. In these two technologies, the main objective is to recover the protein content of the animal's muscle in order for it to be incorporated into animal feed formulations or in the production of flavourings and protein ingredients [67,68].

Table 7 summarises the industrial processes and technologies described above, as well as the ABPs used as raw materials in each process, the final products and their possible uses.

Table 7. Summary of the industrial processes and technologies for the valorisation of muscle, bones and fats.

Industrial Process	Technology	Raw Materials	Final Products	Possible Uses of the Final Products	References
Rendering	Digestion (133 °C; 3 bar; 20 min) for sterilisation and stabilisation of ABPs	Muscle Bones Fats	ABP meal Animal fat	Animal feed Biodiesel production	[59,60]
BioRefinex	Thermal hydrolysis (180 °C; 12 bar; 40 min) + anaerobic digestion (50–60 °C; 10–35 days)	Muscle Bones Fats	Hydrolysed proteins Biogas	Fertilisers Fuels	[61]
Gelatine production	Alkaline pre-treatment + thermal hydrolysis (50–100 °C; 10–36 h)	Bones	Gelatine powder	Food products Pharmaceuticals Photographic products	[64,65]
Chondroitin sulphate production	Enzymatic hydrolysis (60 °C; 8 h; alcalase) + alkaline hydrolysis (35 °C; 1 h; pH > 11)	Bones	Chondroitin sulphate powder	Pharmaceuticals Cosmetics Animal feed	[66]
	Pyrolysis (850 °C; 20 min)	Bones	Bio-char Bio-oil Pyrolysis gas	Fertilisers and adsorbents Fuels	[62]
	Thermal hydrolysis (90–110 °C; 0.5–10 h)	Muscle	Meat extract Meat powder	Meat flavourings Animal feed	[67]
	Enzymatic hydrolysis (50–52 °C; 50 min; papain)	Muscle	Protein powder	Animal feed	[68]

There are several technologies which allow for the processing of animal by-products into animal feed. The rendering process and hydrolysis are the most utilised and use mainly muscle by-products. The extraction of the protein content allows the production of food for animals. Regarding fats, up-scaled technologies address the production of biodiesel and are exclusively focused on that. The enzymatic hydrolysis process can derive different final products depending on the initial by-product. For example, if feed is meat and muscle, it allows for the extraction of the protein content and the production of animal food. When bone feedstocks are considered, chondroitin powders are produced which have multiple applications across the pharmaceutical and cosmetic production industries. The flexibility of the hydrolysis process alongside the fine tuning of operational parameters constitutes the biggest benefits of this process.

5.3. Emerging Low-TRL Systems

Due to the greater concern with the management of resources and the reduction of environmental impacts caused by the production, deposition at landfills and incineration of residues and by-products, there are several research studies that address the use of ABPs in the production and extraction of added-value products [69,70]. Figure 10 synthesises the valorisation procedures for the ABPs generated in the food retail sector—fats, bones and muscle.

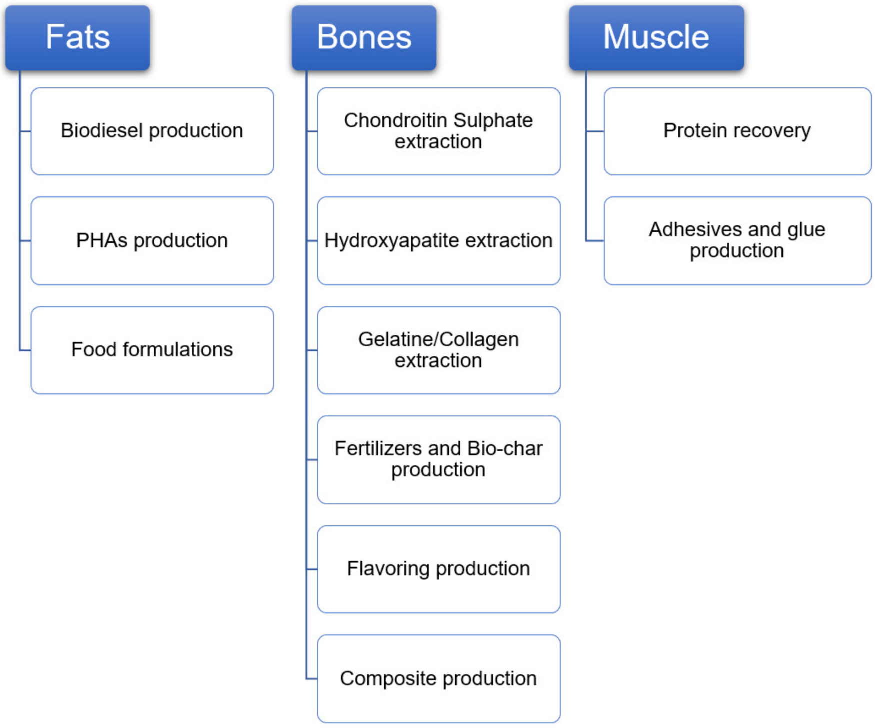

Figure 10. Possible valorisations for the animal by-products generated in the retail sector.

5.3.1. Fat Valorisation Systems

Poultry, beef and pork fats have been involved in several biodiesel production processes, being seen as an alternative, cheaper and sustainable raw material for the production of a biodegradable, renewable and sulphur-free fuel [71]. The most used process for producing biodiesel from animal fats is transesterification. The difference in fat composition among the different animal species is seen in Table 8. Moreira et al. (2015) [72] tested the alkaline transesterification of poultry fat at 30 °C and obtained a biodiesel yield of 81%. The properties of the biodiesel produced fulfilled the European biodiesel quality standard EN 14214, and this experiment allowed for the conclusion that transesterification can occur at low temperatures (T < 70 °C), making it possible to reduce energy and raw material costs.

Table 8. Fat composition of different species.

	H_2O	Proteins	Lipids	Ash	Reference
Poultry	28.7	3.7	67.4	0.3	[73]
Bovine	4	1.5	94.0	0.5	[74]
Pig	7.7	2.9	88.7	0.7	[75]

Emiroğlu et al. (2018) [76] used turkey rendering fat in the production of biodiesel through a two-step reaction (esterification and transesterification), obtaining a final product with an ester content of 96.7% and meeting the EN 14214 and ASTM D6751 standards. The final yield obtained was 88.5%. Marulanda et al. (2010) [77] also tested the production of biodiesel through supercritical transesterification of chicken fat, obtaining an overall yield of 88%. This experiment showed that the transesterification of low-cost lipid feedstocks with low excess of methanol and without generation of glycerol is technically feasible, and it is likely to be used at an industrial scale. It was also concluded that the thermal decomposition of chicken fat is an important factor; however, it was found that this factor was not significant if heated up to 350 °C.

Souissi et al. (2018) [78] tested beef fats as raw material for biodiesel production. In this experiment, enzymatic and chemical transesterification were used, and it was concluded that although the biological method allowed them to obtain a FAME-richer biodiesel, by the chemical method, a biodiesel with better physicochemical properties was obtained. The FAME yield for the biological and chemical methods were 94 and 73%, respectively.

Beef fats were also tested as carbon feedstock in the production of polyhydroxyalkanoates (PHAs), which are biodegradable polyesters considered to be a possible alternative to petroleum-derived plastics. According to Riedel et al. (2015) [79], the production of PHAs involves very high production costs compared to traditional plastics, so using this cheaper raw material would reduce these costs. The final product obtained had high purity (>99%), and a product of 0.4 g PHA/g fat was obtained, showing that it is a process with the potential for industrial application.

According to Amorim et al. (2015) [80], pork fat can be used in food formulations through the winterisation process. This process is a method used to modify the characteristics of oils and fats to provide added value by concentrating the unsaturated fatty acids of the raw materials. The final product obtained in this experiment showed a decrease of approximately 28% in the saturated fatty acid content, and this process improved the quality of the pork fats, reducing the peroxide value and concentrating more than 70% of the unsaturated fatty acids. Table 9 provides technical descriptions of the experimental procedures and main results.

Table 9. Low-TRL systems for animal fat valorisation.

ABP	Final Use	Experimental Procedure	Results	Reference
Poultry Fat	Biodiesel production	Heating (110 °C), filtration (30 °C), transesterification (methanol (6:1) and NaOH (1%); 30 °C; 90 min), decanting (1 h), evaporation (low pressure), mixing (50% (*v*/*v*) HCl (0.2%)), mixing (50% (*v*/*v*) H_2O), dehydration (Na_2SO_4 (25%); 30 rpm), filtration	$\eta_{extraction}$ = 40% $\eta_{biodiesel}$ = 87%	[72]
		Rendering, filtration, heating (110 °C; 1 h), esterification (methanol (40%) + H_2SO_4 (2.5%); 63 °C; 1 h), decanting, mixing (H_2O; 65 °C), heating (110 °C), transesterification (methanol (20%) + KOH (1%)), decanting, mixing (H_2O; 65 °C), heating (110 °C)	$\eta_{biodiesel}$ = 88.5%	[76]
		Rendering, mixing (methanol (6:1)), supercritical transesterification (400 °C; 41.1 MPa; 6 min)	$\eta_{biodiesel}$ = 88%	[77]
Beef Fat	PHA production	PHAs—polyhydroxyalkanoates Rendering, fermentation (30 °C; pH = 6.8; aeration = 0.5 vvm; C_{O2} = 40%; 300–1200 rpm)	Purity >99% Production = 0.4 g PHA/g fat Productivity = 0.36 g PHA/L.h	[79]
	Biodiesel production	Heating, filtration, transesterification (50 °C; KOH + methanol), decanting, washing (hot water + acetic acid), mixing (methanol), vacuum distillation, dehydration (ethylene glycol)	$\eta_{biodiesel}$ = 73%	[78]
Pork Fat	Food formulations	Winterisation process	Decrease of 28% in the saturated fatty acid content	[80]

5.3.2. Bone Valorisation Systems

Regarding the possible uses of animal bones, they have been used in several processes, such as the extraction of gelatine and hydroxyapatite, the production of flavourings, fertilisers and adsorbents (bone char) and even the production of composites [81,82]. The difference in bone composition among the different animal species is seen in Table 10.

Table 10. Bone composition of different species.

	H_2O	Proteins	Lipids	Ash	Others	Reference
Poultry	51.0	19.0	9.0	15.0	6.0	[83]
Bovine	46.0	19.0	15.0	20.0	-	[65]
Pig	36.6	21.8	17.5	24.1	-	[84]

In the extraction of chondroitin sulphate, Wang et al. (2019) [83] tested two different methods: heat-resin static adsorption extraction and enzymatic extraction. The second method led to better results, obtaining a yield of chondroitin sulphate of 4.3%, while in the first method, it was only 0.14%. Therefore, it was concluded that heat-resin static adsorption extraction is a promising method to produce chondroitin sulphate; however, more investigation is needed in order to increase the process yield.

In the extraction of hydroxyapatite, the most used method is calcination at a temperature of 700 °C or above. Khoo et al. (2015) [85] concluded that these calcination conditions allow for the production of an organic free, crystalline and natural hydroxyapatite from cattle bones. Bee et al. (2019) [86] concluded that the optimal calcination temperature is 700 °C since it allows for the total removal of the organic content while conserving the CO_3^{2-} content of the chicken bones, making the final products liable to be used in bone engineering applications. Azzallou et al. (2022) [87] also used waste bovine bones for synthesizing 1-amidoalkyl-2-naphthols derivatives. For this synthesis, the first step was the extraction of hydroxyapatite from the bones by thermal decomposition at 800 °C for 2 h. Then, the resulting product from the thermal decomposition was loaded with an aqueous solution of zinc chloride ($ZnCl_2$), which was used as a catalyst for synthesizing 1-amidoalkyl-2-naphthols. After optimizing the reaction conditions, it was concluded that with a small amount of catalyst (50 mg $ZnCl_2$/bovine-bone-derived hydroxyapatite), high yields (86–96%) can be obtained with residence times between 25–40 min at a temperature of 80 °C.

Erge et al. (2018) [88] tested the use of chicken bones in the production of gelatine. Therefore, the regular steps of the industrial process of producing gelatine from bovine bones were used at the laboratory scale, and it was concluded that chicken bones can be a good alternative raw material, since the obtained gelatine had properties similar to the commercial one. Hosseini-Parvar et al. (2009) [89] used an enzymatic treatment of cattle bones with neutrase before the extraction of gelatine. After optimizing the operating conditions of this treatment, an overall yield of 13.9% was obtained. Etxabide et al. (2017) [90] also highlighted the use of pig and bovine bones as raw material for gelatine production in order to develop active gelatine films that can be further used in the packaging industry [91].

Animal bones can also be used in the production of adsorbents, namely bio-char, and the most used procedure is pyrolysis. Shahid et al. (2019) [92] and Patel et al. (2015) [93] used the pyrolysis process in cattle bones, and the final products obtained showed an adsorption capacity of 10.6 mg F/g adsorbent and a percentage of 17-β oestradiol removal from water of 41.4%. These two procedures showed interesting results for possible environmental applications.

A similar process was used by Deydier et al. (2005) [94], in which chicken bones were subjected to double calcination in order to be further used as fertilisers. The coal produced had 56.4% phosphates and 30.7% calcium in its composition, which makes it a compound with high agro-economic efficiency for use as agricultural fertiliser.

Pig bones were also used in the production of bio-char through a three-step process, which included pre-charring under mild conditions, acid treatment with H_2SO_4 or H_3PO_4 and thermal activation (pyrolysis). In this process, the maximum conversion yield obtained was 68.3%, and the final product was tested on the adsorption of methylene blue in order to determine the impregnation ratios of the acid treatment [95].

Harish et al. (2018) [96] also used bovine bones in particulate-reinforced epoxy composite, which is widely used in industrial applications (aerospace, automotive, biomedical) due to its high strength with lower weight. The carbonised bone particles were incorporated into the reinforcement at different mass fractions (5 to 25%). It was concluded that the tensile and flexural strength increase up to 15%, and the use of carbonised bone particles allows for better strength properties than those of the reinforcement with non-carbonised bone particles.

Wang et al. (2016) [97] tested the use of chicken bones in the production of flavourings through hot pressure extraction (HPE). Regarding the percentage of protein and amino acid recovery, it was concluded that the HPE procedure is a promising process for the production of flavourings from bones. However, it is an inefficient process in the extraction of calcium since the calcium content in the flavouring produced was 4.8 mg/100 g, whereas in bones it is 1078 mg/100 g. Table 11 provides technical descriptions of the experimental procedures for the valorisation of animal bones.

5.3.3. Muscle Valorisation Systems

The muscle, which corresponds to the edible part of the animal, is mostly used to recover its protein content, which can be further used in food formulations, including flavourings, protein supplements and animal feed [98]. Table 12 contains the composition of muscle of the different animal species. The main method used at the laboratory scale is hydrolysis, which can be acidic, alkaline or enzymatic.

Regarding the enzymatic hydrolysis method, Nchienzia et al. (2010) [101] used poultry meal and concluded that the use of a combination of endopeptidase (alcalase) and exopeptidase (flavourzyme) allows for better hydrolysis results than its separate operation, obtaining a degree of hydrolysis of 11.13% and 58% recovery of hydrolysed material. Therefore, this method allows for the production of inexpensive hydrolysed poultry meal, which can be used in animal food products. Kurozawa et al. (2008) [102] also performed the enzymatic hydrolysis of chicken muscle, obtaining a fraction of hydrolysed proteins of 31% and a recovery of 91% of the proteins. The final product obtained showed good application as a protein supplement.

The procedure followed by Stiborova et al. (2020) [103], in addition to laboratory scale, was scaled up, and similar results were obtained. The final product presented the following composition: 77% proteins, 9% chondroitin sulphate, 7% hyaluronic acid and 4% amino acids. It has a commercial value of 88 USD/kg (approximately 73 EUR/kg). Saiga et al. (2003) [104] also studied the inhibitory effect of enzymes in chicken breast after double enzymatic hydrolysis with aspergillus and trypsin. The hydrolysed extract showed stronger inhibitory activity than the chicken extract without hydrolysis (1.1 mg% and 1060 mg%, respectively), and when applied to rats, it allowed for the reduction of their blood pressure by 50 mm Hg.

According to Wang et al. (2018) [105], enzymatic hydrolysis was also performed on turkey muscle, and it was concluded that flavourzyme is an effective enzyme for the preparation of antioxidant hydrolysate from turkey meat, which can be used as a functional ingredient in food formulations.

To improve the enzymatic hydrolysis method, Thoresen et al. (2020) [106] studied the effect of pre-treatments in enhancing the properties of the hydrolysate product. On the one hand, it was concluded that the microwave pre-treatment, by affecting the protein structure, promoted its solubility, and the ultrasound pre-treatment promoted the antioxidant properties of the hydrolysate proteins. On the other hand, the high-pressure pre-treatment induced not only the antioxidant properties but also the protein solubility when a pressure between 100 and 200 MPa was applied.

Selmane et al. (2008) [107] used the thermal hydrolysis method to recover the protein content of poultry muscle, and the obtained hydrolysate was purified and concentrated by successive microfiltration and ultrafiltration. An extraction yield of 83% was obtained; however, the overall yield of the process was 55%. This method was shown to be a good alternative for the extraction of proteins from animal by-products since it allowed for the maintenance of the functional properties of the extracted proteins.

Table 11. Low-TRL systems for animal bone valorisation.

ABP	Final Use	Experimental Procedure	Results	Reference
Poultry Bones	Chondroitin sulphate extraction	Washing (H_2O; 30 min), mixing (H_2O (1.5:1)), heating (120 °C; 0.1 MPa; 120 min), filtration (100-mesh sieve), centrifugation, heat-resin static adsorption extraction, mixing (trichloroacetic acid (7% *w*/*v*); 4°C; 24 h), centrifugation (15,000× *g*; 20 min), mixing (ethanol (70% *v*/*v*); 24 h), centrifugation (5000× *g*; 5 min), drying (60 °C), mixing (H_2O), ultrafiltration, freeze drying	η_{CS} = 0.14% % recovered = 67.4% M_{CS} = 35.81 kDa	[83]
		Crushing, washing (acetone), filtration, drying (60 °C; 24 h), mixing (H_2O (1.5:1) + trypsin), extraction (47 °C; 6 h), heating (10 min), filtration (100-mesh sieve), centrifugation (12,000× *g*; 10 min), mixing (ethanol (70%); 4 °C; 24 h), centrifugation (5000× *g*; 5 min), drying (60 °C)	η_{CS} = 4.25% M_{CS} = 37.18 kDa	
	Hydroxyapatite extraction	Washing, drying (oven), crushing, calcination (electric furnace; P_{atm}; 700 °C)	% lost mass = 28.72%	[86]
	Flavouring production	Crushing, washing (H_2O (1.5:1); 10 min), hot pressure extraction (H_2O; 135 °C; 120 min), filtration (200-mesh sieve), centrifugation (16,000× *g*), evaporation (0.08–0.1 MPa; until 30% solids)	% recovery: Proteins = 83.51% Collagen = 96.81% Amino acids = 31.03–47.73% C_{Ca} = 4.2–4.8 mg/g	[97]
	Gelatine and collagen extraction	Crushing (1–2 mm), mixing (H_2O (1 g:2 mL)), heating (35 °C; 1 h), washing (H_2O), filtration, acid treatment (HCl (1 g:2 mL); 10 °C; 24 h), washing (H_2O), filtration, alkaline treatment (NaOH (1 g: 4 mL; T_{room}; 48 h), mixing (phosphoric acid until pH = 4), washing (H_2O), filtration, mixing (H_2O (1 g: 3 mL); 76–82 °C; 105–183 min), centrifugation (5000 g; 30 °C; 30 min), drying (oven; 42 °C)	Gel strength = 1175.8 g $T_{melting}$ = 33.71 °C $T_{gelling}$ = 25.15 °C	[88]
	Fertiliser production	Dehydration (110 °C; 4–5 h), rendering (133 °C; 3 bar; 20 min), double calcination (electric furnace; 550 °C)	Coal represents 24% of initial poultry meal mass Coal: 56.33% phosphate 30.7% calcium	[94]
Pig Bones	Bio-char production	Crushing (2–5 cm), precarbonisation (450 °C; N_2 atmosphere; 10 °C/min), crushing (0.25–0.35 mm), pyrolysis (800 °C), washing (H_2O)	H = 68.3%	[95]
Bovine Bones	Bio-char production	Washing (H_2O, 90 °C; 24 h), pyrolysis (350 °C; 2 h), cooling (T_{room}), crushing (75–300 µm)	Adsorption capacity = 10.56 mg F/g	[92]
		Washing, drying (110 °C), crushing (1–2 mm), washing (acetone + H_2O), filtration, drying, pyrolysis (400 °C; 2 h; 10.2 °C/min)	Removal of 41.4% of 17-β oestradiol from water	[93]
	Composite production	Crushing, washing (H_2O), drying, carbonisation (550 °C; 1 h), crushing (100 µm)	Composite strength increases with bone carbonisation	[96]
	Hydroxyapatite extraction	Washing (H_2O; 1 h), washing (acetone; 2 h), drying, crushing (45–125 µm), calcination (T; 3 h; 10 °C/min)	Optimal calcination temperature ≥700 °C	[85]
	Gelatine extraction	Crushing (1–3 mm), washing (H_2O), demineralisation (HCl (50 g/L); 8 °C; 2 h), washing (H_2O), enzymatic treatment (neutrase; pH = 9; 50 °C), heating (100 °C), mixing (pH = 7), gelatine extraction (T; 3 h), centrifugation (30 °C; 900× *g*), vacuum filtration, mixing ($Ca(OH)_2$ until pH = 9), flocculation, centrifugation, ion exchange	H = 13.9% Gel strength = 243.22 g µ = 4.915 cP	[89]

Table 12. Muscle composition of different species.

	H_2O	Proteins	Lipids	Ash	Reference
Poultry	75.0	22.8	1.0	1.2	[99]
Bovine	75.1	19.2	4.4	1.3	[100]
Pig	75.1	22.8	1.2	1	[75]

The isoelectric solubilisation/precipitation (ISP) method was performed by Tahergorabi et al. (2012) [108] to recover proteins from poultry meat. This method induces structural changes in some proteins, namely actin; however, the addition of TiO_2 allows for restructuring the products based on the proteins recovered by this method, leading to the formation of a potential new food product, which has to be further subjected to several studies such as sensory and storage stability tests.

Chicken muscle was also used at the laboratory scale for the production of adhesives/glues. According to Wang et al. (2012) [109], after several alkaline and acidic treatments for protein extraction, the product obtained was mixed with a solvent in order to form the adhesive. Sodium dodecyl sulphate (3 M) and urea (3%) were the solvents whose produced adhesives had the best performance.

Regarding the beef and pork muscles, there are not many research studies on the valorisation and use of these animal by-products. However, it is mentioned in the literature that the main destination of these materials is indeed the rendering process [5,50]. According to this, the Lifevalporc project [110] uses pig carcasses; after rendering sterilisation, the pork fat is sent to the biodiesel production process, and the remaining material is sent to the anaerobic digestion process for the production of organic fertilisers. Table 13 provides technical descriptions of the experimental procedures for the valorisation of animal muscle.

Table 13. Low-TRL systems for animal muscle valorisation.

ABP	Final Use	Experimental Procedure	Results	Reference
Poultry Muscle	Protein recovery (hydrolysis)	Rendering, mixing (H_2O), enzymatic hydrolysis (7 h; 50 °C; pH adjustment with NaOH (5.4 M)), heating (85 °C; 15 min), centrifugation (1000× *g*; 4 °C; 30 min), freeze drying (0.045 mbar; −44 °C) Enzymes: alcalase (pH = 8) and flavourzyme (pH = 7)	% hydrolysed = 11.13% % recovered = 58.1%	[101]
		Sterilisation (121 °C; 15 min), enzymatic hydrolysis (phosphate buffer (50 mM); 50–56 °C; 18 h), filtration, centrifugation (15000 rpm; 30 min), filtration, spray drying (67 °C; 4 h) Enzyme: papain	$C_{proteins}$ = 768 mg/g C_{CS} = 89.6 mg/g C_{HA} = 73.9 mg/g $C_{amino\ acids}$ = 44.2 mg/g	[103]
		Crushing, mixing (H_2O (3:1) + NaOH), heating, enzymatic hydrolysis (52.5 °C; pH = 8 with addition of NaOH), heating (85 °C; 20 min), centrifugation (3500rpm; 20 min) Enzyme: alcalase (4.2%)	% hydrolysed protein = 31% % recovered protein = 91%	[102]
		Crushing (3000 rpm; 3 min), mixing (H_2O; 1100 rpm; 5 min), hydrolysis (40 °C; pH = 9; 60 min), centrifugation (10,000× *g*; 15 min), microfiltration (2 bar), ultrafiltration (2 bar), isoelectric precipitation (HCl (37%) until pH = 4), centrifugation (5000× *g*; 5 min), mixing (hexane + isopropanol (3:2 *v*/*v*); 1 h; 20 °C), evaporation	$\eta_{extraction}$ = 83% $\eta_{process}$ = 55%	[107]
		Crushing (2.3 mm), ISP (H_2O + TiO_2 (6:1); 32–34 °C), mixing (NaOH until pH = 11.5; 10 min), centrifugation (10,000× *g*; 10 min), mixing (HCl until pH = 5.5; 10 min), centrifugation	Addition of TiO_2 to the ISP-recovered proteins resulted in increased gel strength	[108]
		Mixing (H_2O; pH = 4–4.5; 3.5 h), filtration, centrifugation, evaporation (until 25° Brix), enzymatic hydrolysis (aspergillus (0.06%); 50 °C; pH = 7; 1 h), heating (10 min), enzymatic hydrolysis (trypsin/chymotrypsin (1%); 37 °C; pH = 7; 1 h), heating (10 min), centrifugation	Inhibitory activity: Chicken extract = 1060 mg% Hydrolysed extract = 1.1 mg%	[104]
	Adhesive and glue production	Mixing (H_2O (1:4 *w*/*v*); 10 min), filtration (200-mesh sieve), centrifugation (10,000× *g*; 4 °C; 25 min), mixing (NaOH (2 M) until pH = 11), centrifugation (10,000× *g*; 4 °C; 25 min), mixing (HCl (2 M) until pH = 5), centrifugation, washing (H_2O), freeze drying, mixing (sodium dodecyl sulphate (3 M) or urea (3%) and NaOH (10%) until pH = 10)	Urea (3%)/SDS (3 M): Dry strength = 7.99/9.35 MPa Wet strength = 3.35/2.9 MPa Soaked strength = 5.21/8.89 MPa	[109]

6. Conclusions

The work developed allows for the identification and characterisation of the main alternatives for the valorisation of ABPs generated in the retail sector in a context of industrial symbiosis.

One of the products that has a major contribution not only to the food waste problem but also to the environmental impacts of the agri-food business is meat. Although world meat consumption is increasing, approximately 20% of the meat available for consumption is wasted. In Europe, 14.1 Mt of meat is wasted every year, of which 76% occurs in the final stages of the supply chain, with the processing and retail sector contributing 33% of the European meat waste. These data highlight the importance of finding alternatives for the better use and valorisation of the ABPs generated in the retail sector—muscle, bones and fats. According to the European Union Regulation 1069/2009, these ABPs are included in category 3, which is the lowest risk category.

On an industrial scale, the most used process in the management of all ABPs is rendering, in which the stabilisation and sterilisation of these materials occur under severe conditions of temperature and pressure. Its two main final products are animal meal and animal fat, which can be used as animal feed and for biodiesel production, respectively. The *BioRefinex* process also incorporates muscle, bones and fats, where the combination of thermal hydrolysis and anaerobic digestion allows for the production of organic fertilisers and biogas. Regarding the valorisation of bones, the main valorisation alternatives are pyrolysis in the production of agricultural fertilisers and the gelatine and chondroitin sulphate production processes. Muscle has thermal and enzymatic hydrolysis as its main destinations for the extraction of proteins, which in turn can be incorporated into food formulations or animal feed.

Due to the greater concern with the management of resources and the reduction of environmental impacts caused by the production, deposition at landfills and incineration of residues and by-products, there are several low-TRL systems that address the use of ABPs in the production and extraction of added-value products. The approaches for the valorisation of fats are mainly related to the production of biodiesel, and for the bones, the extraction of chondroitin sulphate and hydroxyapatite, as well as the production of bio-char, which can be used as an adsorbent in the treatment of wastewater or as fertiliser. The valorisation of the muscular part is related to the extraction and recovery of its protein content through hydrolysis procedures. It is also concluded that the valorisation procedures do not depend on the animal itself, being coincident for all types of animals under study—poultry, cattle and pigs.

Concerning all the low-TRL systems and industrial procedures analysed, it can also be concluded that there is great potential for the valorisation of these animal by-products, which is evidenced by the diversity of possible applications as well as the variety of procedures that can be adopted to obtain similar final products.

Practical Implications

Despite several efforts in developing new technologies or technical pathways for the valorisation of animal by-products, much remains to be done. On one hand, industrial-scale processes such as the ones presented in Table 7 should be incentivised such that they become widely applied. These technologies provide the opportunity to close loops in the food supply chain with the production of organic fertilisers, substituting mineral ones, and the production of biofuel and value-added products. Government and municipalities can take on a prominent role if they actively participate in collaborating to provide access to municipalised infrastructures, such as anaerobic digestors and incineration facilities. There could be an interest as well in developing effective integrated logistics for the collection and treatment of waste at the municipal level. On the other hand, low-TRL technologies look promising, although currently still lacking in pilot testing. Therefore, testing these technologies at pilot scale so that new insights can be made in the technical and economic feasibility of the technologies could provide an important step toward meat valorisation into new value-added products. For this, collaboration with retailers, municipalities, biorefineries and technology deployers is recommended.

Author Contributions: Conceptualisation, R.B.-D. and H.A.M.; Data curation, J.P.; Formal analysis, J.P., R.B.-D. and H.A.M.; Investigation, J.P.; Methodology, J.P. and R.B.-D.; Resources, H.A.M.; Validation, J.A.; Visualisation, J.A.; Writing—original draft, J.P.; Writing—review and editing, R.B.-D., H.A.M. and J.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the reviewers for the comments and suggestions which helped to improve the current work.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Food and Agriculture Organization of the United Nations. *Food Loss and Food Waste: Extent, Causes and Solutions*; FAO: Rome, Italy, 2011. [CrossRef]
2. Stenmarck, Å.; Jensen, C.; Quested, T.; Moates, G.; Cseh, B.; Juul, S.; Parry, A.; Politano, A.; Redlingshofer, B.; Scherhaufer, S.; et al. *FUSIONS—Estimates of European Food Waste Levels*; IVL Swedish Environmental Research Institute: Stockholm, Sweden, 2016.
3. Mathijs, E. Exploring future patterns of meat consumption. *Meat Sci.* **2015**, *109*, 112–116. [CrossRef] [PubMed]
4. Hawkesworth, S.; Dangour, A.D.; Johnston, D.; Lock, K.; Poole, N.; Rushton, J.; Uauy, R.; Waage, J. Feeding the world healthily: The challenge of measuring the effects of agriculture on health. *Philos. Trans. R. Soc. B Biol. Sci.* **2010**, *365*, 3083–3097. [CrossRef] [PubMed]
5. Toldrá, F.; Mora, L.; Reig, M. New insights into meat by-product utilization. *Meat Sci.* **2016**, *120*, 54–59. [CrossRef] [PubMed]
6. Roka, K. Environmental and Social Impacts of Food Waste. In *Responsible Consumption and Production*; Springer: Cham, Switzerland, 2019; pp. 1–13. [CrossRef]
7. Gerber, P.J.; Steinfeld, H.; Henderson, B.; Mottet, A.; Opio, C.; Dijkman, J.; Falcucci, A.; Tempio, G. *Tackling Climate Change through Livestock—A Global Assessment of Emissions and Mitigation Opportunities*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2013.
8. Caldeira, C.; De Laurentiis, V.; Corrado, S.; van Holsteijn, F.; Sala, S. Quantification of food waste per product group along the food supply chain in the European Union: A mass flow analysis. *Resour. Conserv. Recycl.* **2019**, *149*, 479–488. [CrossRef] [PubMed]
9. Lombardi, D.R.; Laybourn, P. Redefining Industrial Symbiosis. *J. Ind. Ecol.* **2012**, *16*, 28–37. [CrossRef]
10. Chertow, M.R. Uncovering' Industrial Symbiosis. *J. Ind. Ecol.* **2007**, *11*, 11–30. [CrossRef]
11. Turon, X.; Venus, J.; Arshadi, M.; Koutinas, M.; Lin, C.S.K.; Koutinas, A. Food Waste and Byproduct Valorization through Bio-processing: Opportunities and Challenges. *BioResources* **2014**, *9*, 5774–5777. [CrossRef]
12. Xiong, X.; Yu, I.K.; Tsang, D.; Bolan, N.; Ok, Y.S.; Igalavithana, A.D.; Kirkham, M.B.; Kim, K.-H.; Vikrant, K. Value-added chemicals from food supply chain wastes: State-of-the-art review and future prospects. *Chem. Eng. J.* **2019**, *375*, 121983. [CrossRef]
13. Xu, F.; Li, Y.; Ge, X.; Yang, L.; Li, Y. Anaerobic digestion of food waste—Challenges and opportunities. *Bioresour. Technol.* **2018**, *247*, 1047–1058. [CrossRef]
14. Girotto, F.; Alibardi, L.; Cossu, R. Food waste generation and industrial uses: A review. *Waste Manag.* **2015**, *45*, 32–41. [CrossRef]
15. Muriana, C. A focus on the state of the art of food waste/losses issue and suggestions for future researches. *Waste Manag.* **2017**, *68*, 557–570. [CrossRef] [PubMed]
16. Bhattacharya, A.; Nand, A.; Prajogo, D. Taxonomy of antecedents of food waste—A literature review. *J. Clean. Prod.* **2021**, *291*, 125910. [CrossRef]
17. European Commission. Directive 2008/98/EC on waste and repealing certain directives (Waste Framework Directive). *Off. J. Eur. Union* **2008**, *34*, 3–30. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:312:0003:0030:en:PDF (accessed on 20 December 2020).
18. Gunderson, M.; Boehlje, M.; Neves, M.; Sonka, S. Agribusiness Organization and Management. *Encycl. Agric. Food Syst.* **2014**, *1*, 51–70. [CrossRef]
19. Papargyropoulou, E.; Lozano, R.; Steinberger, J.; Wright, N.; bin Ujang, Z. The food waste hierarchy as a framework for the management of food surplus and food waste. *J. Clean. Prod.* **2014**, *76*, 106–115. [CrossRef]
20. Goedde, L.; Horil, M.; Sanghvi, S. *Pursuing the Global Opportunity in Food and Agribusiness*; Mckinsey Quarterly: Atlanta, GA, USA, 2015.

21. FoodDrink Europe. Data & Trends of the European Food and Drink Industry. 2011. Available online: https://www.fooddrinkeurope.eu/wp-content/uploads/2021/11/FoodDrinkEurope-Data-Trends-2021-digital.pdf (accessed on 20 December 2020).
22. Manning, L.; Baines, R.; Chadd, S. Deliberate contamination of the food supply chain. *Br. Food J.* **2005**, *107*, 225–245. [CrossRef]
23. Cicatiello, C.; Franco, S.; Pancino, B.; Blasi, E.; Falasconi, L. The dark side of retail food waste: Evidences from in-store data. *Resour. Conserv. Recycl.* **2017**, *125*, 273–281. [CrossRef]
24. Canali, M.; Amani, P.; Aramyan, L.; Gheoldus, M.; Moates, G.; Östergren, K.; Silvennoinen, K.; Waldron, K.; Vittuari, M. Food Waste Drivers in Europe, from Identification to Possible Interventions. *Sustainability* **2017**, *9*, 37. [CrossRef]
25. Food and Agriculture Organization of the United Nations. Technical Platform on the Measurement and Reduction of Food Loss and Waste. 2020. Available online: http://www.fao.org/platform-food-loss-waste/en/ (accessed on 20 July 2020).
26. Fahrenkamp-Uppenbrink, J. Reducing food loss and waste. *Science* **2016**, *352*, 424–426. [CrossRef]
27. Vilariño, M.V.; Franco, C.; Quarrington, C. Food loss and Waste Reduction as an Integral Part of a Circular Economy. *Front. Environ. Sci.* **2017**, *5*, 21. [CrossRef]
28. Food and Agriculture Organization of the United Nations. *Food Wastage Footprint—Impacts on Natural Resources*; FAO: Rome, Italy, 2013. Available online: https://www.fao.org/3/i3347e/i3347e.pdf (accessed on 20 December 2020).
29. Katsarova, I. *Tackling Food Waste: The EU's Contribution to a Global Issue*; No. November; European Parliamentary Research Service: Brussels, Belgium, 2016.
30. European Commission. *Preparatory Study on Food Waste across EU 27*; No. October; European Commission: Brussels, Belgium, 2010; Volume 33. [CrossRef]
31. Grethe, H.; Dembele, A.; Duman, N. *How to Feed the World's Growing Billions—Understanding FAO World Food Projections and their Implications*; Heinrich Böll Stiftung: Berlin, Germany; WWF: Washington, DC, USA, 2011. Available online: https://www.wwf.de/fileadmin/user_upload/WWF_BOELL_How_to_feed.pdf (accessed on 20 January 2021).
32. Priefer, C.; Jörissen, J.; Bräutigam, K.-R. *Technology Options for Feeding 10 Billion People—Options for Cutting Food Waste*; European Union: Brussels, Belgium, 2013; Available online: https://www.europarl.europa.eu/RegData/etudes/etudes/join/2013/513515/IPOL-JOIN_ET(2013)513515_EN.pdf (accessed on 20 January 2021).
33. Waarts, Y.; van der Sluis, A.; Timmermans, T. Obstacles Experienced in Legislation and Regulations, No. October. 2015. Available online: https://library.wur.nl/WebQuery/wurpubs/fulltext/188798 (accessed on 20 December 2020).
34. De Hooge, I.E.; van Dulm, E.; van Trijp, H.C.M. Cosmetic specifications in the food waste issue: Supply chain considerations and practices concerning suboptimal food products. *J. Clean. Prod.* **2018**, *183*, 698–709. [CrossRef]
35. Raak, N.; Symmank, C.; Zahn, S.; Aschemann-Witzel, J.; Rohm, H. Processing- and product-related causes for food waste and implications for the food supply chain. *Waste Manag.* **2017**, *61*, 461–472. [CrossRef]
36. Stenmarck, Å.; Hanssen, O.J.; Werge, M.; Silvennoinen, K.; Katajajuuri, J.-M. *Initiatives on Prevention of Food Waste in the Retail and Wholesale Trades*; Nordic Council of Ministers: Stockholm, Sweden, 2011. [CrossRef]
37. Eriksson, M.; Strid, I.; Hansson, P.-A. Food waste reduction in supermarkets—Net costs and benefits of reduced storage temperature. *Resour. Conserv. Recycl.* **2016**, *107*, 73–81. [CrossRef]
38. Eriksson, M.; Strid, I.; Hansson, P.-A. Waste of organic and conventional meat and dairy products—A case study from Swedish retail. *Resour. Conserv. Recycl.* **2014**, *83*, 44–52. [CrossRef]
39. Engström, R.; Carlsson-Kanyama, A. Food losses in food service institutions Examples from Sweden. *Food Policy* **2004**, *29*, 203–213. [CrossRef]
40. Parfitt, J.; Barthel, M.; Macnaughton, S. Food waste within food supply chains: Quantification and potential for change to 2050. *Philos. Trans. R. Soc. B Biol. Sci.* **2010**, *365*, 3065–3081. [CrossRef]
41. Monforti-Ferrario, F.; Dallemand, J.; Pinedo Pascua, I.; Motola, V.; Banja, M.; Scarlat, N.; Medarac, H.; Castellazzi, L.; Labanca, N.; Bertoldi, P.; et al. *Energy Use in the EU Food Sector: State of Play and Opportunities for Improvement*; Publications Office of the European Union: Luxemburg, 2015.
42. Mekonnen, M.M.; Hoekstra, A. A Global Assessment of the Water Footprint of Farm Animal Products. *Ecosystems* **2012**, *15*, 401–415. [CrossRef]
43. Hoekstra, A.Y.; Mekonnen, M.M. The water footprint of humanity. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 3232–3237. [CrossRef]
44. Food and Agriculture Organization of the United Nations. *Food Wastage Footprint—Full-Cost Accounting*; FAO: Rome, Italy, 2014.
45. Kanani, F.; Heidari, M.D.; Gilroyed, B.H.; Pelletier, N. Waste valorization technology options for the egg and broiler industries: A review and recommendations. *J. Clean. Prod.* **2020**, *262*, 121129. [CrossRef]
46. González, N.; Marquès, M.; Nadal, M.; Domingo, J.L. Meat consumption: Which are the current global risks? A review of recent (2010–2020) evidences. *Food Res. Int.* **2020**, *137*, 109341. [CrossRef]
47. OECD. *Meat Consumption (Indicator)*; Organisation for Economic Co-operation and Development: Paris, France, 2020. [CrossRef]
48. Westhoek, H.; Rood, T.; van den Berg, M.; Janse, J.; Nijdam, D.; Reudink, M.; Stehfest, E.; Lesschen, J.P.; Oenema, O.; Woltjer, G.B. *The Protein Puzzle—The Consumption and Production of Meat, Dairy and Fish in the European Union 2011*; Netherlands Environmental Assessment Agency: The Hague, The Netherlands, 2011.
49. Toldrá, F.; Aristoy, M.-C.; Mora, L.; Reig, M. Innovations in value-addition of edible meat by-products. *Meat Sci.* **2012**, *92*, 290–296. [CrossRef]

50. European Commission. Regulation (EC) No 1069/2009 Laying Down Health Rules as Regards Animal by-Products and Derived Products Not Intended for Human Consumption and Repealing Regulation (EC) No 1774/2002—Animal by-products Regulation. *Off. J. Eur. Union* **2009**, *300*, 1–33.
51. European Commission. Regulation (EU) No 142/2011 of 25 February 2011 Implementing Regulation (EC) No 1069/2009 of the European Parliament and of the Council Laying Down Health Rules as Regards Animal by-Products and Derived Products Not Intended for Human Consumption. *Off. J. Eur. Union* **2011**, *54*, 1–254.
52. European Commission. Regulation (EC) No 999/2001 laying down rules for the prevention, control and eradication of certain transmissible spongiform encephalopathies. *Off. J. Eur. Union* **2001**, *147*, 1–40.
53. European Commission. Guidelines for the feed use of food no longer intended for human consumption (2018/C 133/02). *Off. J. Eur. Union* **2018**, *133*, 2–18.
54. Chertow, M.R. Industrial symbiosis: Literature and Taxonomy. *Annu. Rev. Energy Environ.* **2000**, *25*, 313–337. [CrossRef]
55. Fraccascia, L.; Magno, M.; Albino, V. Business models for industrial symbiosis: A guide for firms. *Procedia Environ. Sci. Eng. Manag.* **2016**, *3*, 83–93.
56. Neves, A.; Godina, R.; Azevedo, S.G.; Matias, J.C.O. A comprehensive review of industrial symbiosis. *J. Clean. Prod.* **2020**, *247*, 119113. [CrossRef]
57. Lowe, E.A. Creating by-product resource exchanges: Strategies for eco-industrial parks. *J. Clean. Prod.* **1997**, *5*, 57–65. [CrossRef]
58. Adhikari, B.B.; Chae, M.; Bressler, D.C. Utilization of Slaughterhouse Waste in Value-Added Applications: Recent Advances in the Development of Wood Adhesives. *Polymers* **2018**, *10*, 176. [CrossRef] [PubMed]
59. Meeker, D.L. *Essential Rendering—All About THE Animal By-Products Industry*; National Renderers Association: Alexandria, VA, USA, 2006.
60. Campos, I.; Valente, L.M.P.; Matos, E.; Marques, P.; Freire, F. Life-cycle assessment of animal feed ingredients: Poultry fat, poultry by-product meal and hydrolyzed feather meal. *J. Clean. Prod.* **2020**, *252*, 119845. [CrossRef]
61. Facey, R.M.; Stavne, A. Apparatus and Process for Production of Biogas. Patent CA 2641270, 25 December 2009.
62. Someus, E.; Pugliese, M. Concentrated Phosphorus Recovery from Food Grade Animal Bones. *Sustainability* **2018**, *10*, 2349. [CrossRef]
63. European Commission. *Communication on the 2017 List of Critical Raw Materials for the EU*; European Commission: Brussels, Belgium, 2017; pp. 1–8.
64. Schrieber, R.; Gareis, H. *Gelatine Handbook—Theory and Industrial Practice*; Wiley: Hoboken, NJ, USA, 2007.
65. European Commission. *Best Available Techniques in the Slaughterhouses and Animal By-Products Industries*; European IPPC Bureau: Seville, Spain, 2005.
66. Chomarat, F.N.; Grech, G.P.; Cueto, L.G.; Rodriguez, E.; Boe, J.-F. Method for the Preparation of Sodium Chondroitin Sulphate. U.S. Patent 2013/0172289 A1, 4 July 2013.
67. Meat and Livestock Australia, "Edible Meat Powders and Extracts." 2001. Available online: https://meatupdate.csiro.au/infosheets/Edible%20Meat%20Powders%20and%20Extracts.pdf (accessed on 20 February 2021).
68. Scheide-Fisher, I.; Scheide, J.D. Method of Manufacturing Meat Extract. U.S. Patent 2011/0250316 A1, 13 October 2011.
69. Toldrá, F.; Reig, M.; Mora, L. Management of meat by- and co-products for an improved meat processing sustainability. *Meat Sci.* **2021**, *181*, 108608. [CrossRef]
70. Mosna, D.; Bottani, E.; Vignali, G.; Montanari, R. Environmental benefits of pet food obtained as a result of the valorisation of meat fraction derived from packaged food waste. *Waste Manag.* **2021**, *125*, 132–144. [CrossRef]
71. Liu, N.; Jiang, J. Valorisation of food waste using salt to alleviate inhibition by animal fats and vegetable oils during anaerobic digestion. *Biomass-Bioenergy* **2020**, *143*, 105826. [CrossRef]
72. Moreira, A.L.; Dias, J.M.; Almeida, M.F.; Alvim-Ferraz, M.C.M.; Alvim-Ferraz, M.D.C. Biodiesel Production through Transesterification of Poultry Fat at 30 °C. *Energy Fuels* **2010**, *24*, 5717–5721. [CrossRef]
73. U.S. Department of Agriculture. Chicken, Broilers or Fryers, Separable Fat, Raw. 2019. Available online: https://fdc.nal.usda.gov/fdc-app.html#/food-details/171468/nutrients (accessed on 3 July 2020).
74. U.S. Department of Agriculture. Beef, Retail Cuts, Separable Fat, Raw. 2019. Available online: https://fdc.nal.usda.gov/fdc-app.html#/food-details/168605/nutrients (accessed on 3 July 2020).
75. Food and Agriculture Organization of the United Nations. "Composition of Meat". 2020. Available online: http://www.fao.org/ag/againfo/themes/en/meat/backgr_composition.html (accessed on 8 July 2020).
76. Emiroğlu, A.O.; Keskin, A.; Şen, M. Experimental investigation of the effects of turkey rendering fat biodiesel on combustion, performance and exhaust emissions of a diesel engine. *Fuel* **2018**, *216*, 266–273. [CrossRef]
77. Marulanda, V.F.; Anitescu, G.; Tavlarides, L.L. Investigations on supercritical transesterification of chicken fat for biodiesel production from low-cost lipid feedstocks. *J. Supercrit. Fluids* **2010**, *54*, 53–60. [CrossRef]
78. Souissi, Y.; Alouini, M.; Mnif, W. Chemical and Biological Investigation of Organic Wastes of Frying Oils and Beef Fats: Valorization for Biodiesel Production. *J. Chem.* **2018**, *2018*, 6248047. [CrossRef]
79. Riedel, S.L.; Jahns, S.; Koenig, S.; Bock, M.C.; Brigham, C.J.; Bader, J.; Stahl, U. Polyhydroxyalkanoates production with Ralstonia eutropha from low quality waste animal fats. *J. Biotechnol.* **2015**, *214*, 119–127. [CrossRef]
80. Amorim, C.D.; Camilo, A.G.; De Oliveira, C.; Petenucci, M.E.; Fonseca, G.G. Turning pork processing waste into value-added chemicals for the food industry. *Sustain. Mater. Technol.* **2015**, *6*, 1–5. [CrossRef]

81. Shirsath, A.P.; Henchion, M.M. Bovine and ovine meat co-products valorisation opportunities: A systematic literature review. *Trends Food Sci. Technol.* **2021**, *118*, 57–70. [CrossRef]
82. O'Connor, J.; Hoang, S.A.; Bradney, L.; Dutta, S.; Xiong, X.; Tsang, D.C.; Ramadass, K.; Vinu, A.; Kirkham, M.; Bolan, N.S. A review on the valorisation of food waste as a nutrient source and soil amendment. *Environ. Pollut.* **2020**, *272*, 115985. [CrossRef]
83. Wang, X.; Shen, Q.; Zhang, C.; Jia, W.; Han, L.; Yu, Q. Chicken leg bone as a source of chondroitin sulfate. *Carbohydr. Polym.* **2018**, *207*, 191–199. [CrossRef] [PubMed]
84. Field, R.A.; Riley, M.L.; Meuo, F.C.; Corbfidge, M.H. Bone composition in cattle, pigs, sheep and poulty. *J. Anim. Sci.* **1974**, *39*, 493–499. [CrossRef]
85. Khoo, W.; Nor, F.; Ardhyananta, H.; Kurniawan, D. Preparation of Natural Hydroxyapatite from Bovine Femur Bones Using Calcination at Various Temperatures. *Procedia Manuf.* **2015**, *2*, 196–201. [CrossRef]
86. Bee, S.-L.; Mariatti, M.; Ahmad, N.; Yahaya, B.; Hamid, Z.A. Effect of the calcination temperature on the properties of natural hydroxyapatite derived from chicken bone wastes. *Mater. Today Proc.* **2019**, *16*, 1876–1885. [CrossRef]
87. Azzallou, R.; Ouerghi, O.; Geesi, M.H.; Riadi, Y.; Taleb, M.A.; Mamouni, R.; Lazar, S.; Kaiba, A.; Kamal, M.; Villain, S. Bovine bone-derived natural hydroxyapatite-supported ZnCl2 as a sustainable high efficiency heterogeneous biocatalyst for synthesizing amidoalkyl naphthols. *J. Phys. Chem. Solids* **2022**, *163*, 110533. [CrossRef]
88. Erge, A.; Zorba, Ö. Optimization of gelatin extraction from chicken mechanically deboned meat residue using alkaline pre-treatment. *LWT* **2018**, *97*, 205–212. [CrossRef]
89. Hosseini-Parvar, S.H.; Keramat, J.; Kadivar, M.; Khanipour, E.; Motamedzadegan, A. Optimising conditions for enzymatic extraction of edible gelatin from the cattle bones using response surface methodology. *Int. J. Food Sci. Technol.* **2009**, *44*, 467–475. [CrossRef]
90. Etxabide, A.; Uranga, J.; Guerrero, P.; de la Caba, K. Development of active gelatin films by means of valorisation of food processing waste: A review. *Food Hydrocoll.* **2017**, *68*, 192–198. [CrossRef]
91. Pramualkijja, T.; Pirak, T.; Euston, S.R. Valorization of chicken slaughterhouse by-products: Production and properties of chicken trachea hydrolysates using commercial proteases. *Int. J. Food Prop.* **2021**, *24*, 1642–1657. [CrossRef]
92. Shahid, M.K.; Kim, J.Y.; Choi, Y. Synthesis of bone char from cattle bones and its application for fluoride removal from the contaminated water. *Groundw. Sustain. Dev.* **2019**, *8*, 324–331. [CrossRef]
93. Patel, S.; Han, J.; Qiu, W.; Gao, W. Synthesis and characterisation of mesoporous bone char obtained by pyrolysis of animal bones, for environmental application. *J. Environ. Chem. Eng.* **2015**, *3*, 2368–2377. [CrossRef]
94. Deydier, E.; Guilet, R.; Sarda, S.; Sharrock, P. Physical and chemical characterisation of crude meat and bone meal combustion residue: "Waste or raw material?". *J. Hazard. Mater.* **2005**, *121*, 141–148. [CrossRef]
95. Iriarte-Velasco, U.; Sierra, I.; Zudaire, L.; Ayastuy, J.L. Preparation of a porous biochar from the acid activation of pork bones. *Food Bioprod. Process.* **2016**, *98*, 341–353. [CrossRef]
96. Harish, S.; Guptha, N.V. The study of tensile and flexural strength of cattle bone particulate reinforced epoxy. *Mater. Today Proc.* **2018**, *5*, 20927–20931. [CrossRef]
97. Wang, J.; Dong, X.; Yue, J.; Zhang, C.; Jia, W.; Li, X. Preparation of Substrate for Flavorant from Chicken Bone Residue with Hot-Pressure Process. *J. Food Sci.* **2016**, *81*, C578–C586. [CrossRef]
98. Lafarga, T.; Hayes, M. Bioactive peptides from meat muscle and by-products: Generation, functionality and application as functional ingredients. *Meat Sci.* **2014**, *98*, 227–239. [CrossRef]
99. Besler, M.; Fiocch, A.; Restani, P. Allergen Data Collection: Chicken Meat (*Gallus domesticus*). *Internet Symp. Food Allerg.* **2001**, *3*, 193–201.
100. Besler, M.; Fiocch, A.; Restani, P. Allergen Data Collection: Beef (*Bos domesticus*). *Internet Symp. Food Allerg.* **2001**, *3*, 171–184.
101. Nchienzia, H.; Morawicki, R.; Gadang, V. Enzymatic hydrolysis of poultry meal with endo- and exopeptidases. *Poult. Sci.* **2010**, *89*, 2273–2280. [CrossRef]
102. Kurozawa, L.; Park, K.J.; Hubinger, M. Optimization of the Enzymatic Hydrolysis of Chicken Meat Using Response Surface Methodology. *J. Food Sci.* **2008**, *73*, C405–C412. [CrossRef]
103. Stiborova, H.; Kronusova, O.; Kastanek, P.; Brazdova, L.; Lovecka, P.; Jiru, M.; Belkova, B.; Poustka, J.; Stranska, M.; Hajslova, J.; et al. Waste products from the poultry industry: A source of high-value dietary supplements. *J. Chem. Technol. Biotechnol.* **2020**, *95*, 985–992. [CrossRef]
104. Saiga, A.; Okumura, T.; Makihara, T.; Katsuta, S.; Shimizu, T.; Yamada, R.; Nishimura, T. Angiotensin I-Converting Enzyme Inhibitory Peptides in a Hydrolyzed Chicken Breast Muscle Extract. *J. Agric. Food Chem.* **2003**, *51*, 1741–1745. [CrossRef] [PubMed]
105. Wang, D.; Shahidi, F. Protein hydrolysate from turkey meat and optimization of its antioxidant potential by response surface methodology. *Poult. Sci.* **2018**, *97*, 1824–1831. [CrossRef] [PubMed]
106. Thoresen, P.P.; Álvarez, R.G.; Vaka, M.R.; Rustad, T.; Sone, I.; Fernández, E.N. Potential of innovative pre-treatment technologies for the revalorisation of residual materials from the chicken industry through enzymatic hydrolysis. *Innov. Food Sci. Emerg. Technol.* **2020**, *64*, 102377. [CrossRef]
107. Selmane, D.; Christophe, V.; Gholamreza, D. Extraction of proteins from slaughterhouse by-products: Influence of operating conditions on functional properties. *Meat Sci.* **2008**, *79*, 640–647. [CrossRef] [PubMed]

108. Tahergorabi, R.; Sivanandan, L.; Jaczynski, J. Dynamic rheology and endothermic transitions of proteins recovered from chicken-meat processing by-products using isoelectric solubilization/precipitation and addition of TiO_2. *LWT* **2012**, *46*, 148–155. [CrossRef]
109. Wang, C.; Wu, J. Preparation and characterization of adhesive from spent hen proteins. *Int. J. Adhes. Adhes.* **2012**, *36*, 8–14. [CrossRef]
110. Lifevalporc. Valorization of Pig Carcasses through Their Transformation into Biofuels and Organic Fertilizers. 2017. Available online: http://lifevalporc.eu/Lifevalporc (accessed on 21 October 2020).