

Review

“What a Waste”—Can We Improve Sustainability of Food Animal Production Systems by Recycling Food Waste Streams into Animal Feed in an Era of Health, Climate, and Economic Crises?

Gerald C. Shurson 

Department of Animal Science, University of Minnesota, St. Paul, MN 55108, USA; shurs001@umn.edu

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Abstract: Food waste has been a major barrier to achieving global food security and environmental sustainability for many decades. Unfortunately, food waste has become an even bigger problem in many countries because of supply chain disruptions during the COVID-19 pandemic and African Swine Fever epidemic. Although Japan and South Korea have been leaders in recycling food waste into animal feed, countries that produce much greater amounts of food waste, such as the United States and the European Union, have lagged far behind. Concerns about the risk of transmission of bacteria, prions, parasites, and viruses have been the main obstacles limiting the recycling of food waste streams containing animal-derived tissues into animal feed and have led to government regulations restricting this practice in the U.S. and EU. However, adequate thermal processing is effective for inactivating all biological agents of concern, perhaps except for prions from infected ruminant tissues. The tremendous opportunity for nitrogen and phosphorus resource recovery along with several other environmental benefits from recycling food waste streams and rendered animal by-products into animal feed have not been fully appreciated for their substantial contribution toward solving our climate crisis. It is time to revisit our global approach to improving economic and environmental sustainability by more efficiently utilizing the abundant supply of food waste and animal tissues to a greater extent in animal feed while protecting human and animal health in food animal production systems.

Keywords: biosecurity; carcass disposal; food waste; greenhouse gas emissions; life cycle assessment; nitrogen; pathogens; phosphorus; rendered animal by-products

1. Introduction

Crises often lead to change [1]. For far too long, food waste has been the greatest contributor to inefficiency of resource use and our inability to achieve greater global food security and sustainability. More than 1.3 billion tonnes of edible food material are wasted annually around the world, which represents about one third of the total food produced and is enough to feed more than one billion people [2]. The amount and types of food waste vary between countries where 44% of global food waste occurs in less-developed countries during the post-harvest and processing stages of the food supply chain, while the remaining 56% of these losses, of which 40% occur at the pre- and post-consumer stages, are attributed to developed countries in Europe, North America, Oceania, Japan, South Korea, and China [2,3]. As a result, the United Nations (UN) has deemed food waste reduction as a global priority and included it in the list of sustainability goals [4]. Specifically, food waste reduction has significant implications for several of the UN Sustainable Development Goals including: 2. Zero hunger; 12. Responsible consumption and production; 13. Climate action; 14. Life below water; and 15. Life on land [4].

Crises often accelerate existing trends [1] and the COVID-19 (novel coronavirus SARS-CoV-2) pandemic is redefining the concept of sustainability [5]. The COVID-19 pandemic has caused major disruptions in food supply chains and caused huge shifts in food access, food security, and food losses due to changes in food flow and distribution patterns [6]. Food supply chains are complex and most operate in a “just-in-time” mode where minor disruptions can have dramatic consequences [7]. When workers were required to stay at home, and all businesses except those deemed essential were closed, consumer demand for food shifted from food services (e.g., restaurants, hotels, schools, and institutions) to retail grocery stores [7]. Although ample supplies of food were available, existing food distribution networks were unable to quickly respond to these changes, which resulted in increased food waste [6]. For example, short-term disruptions in eating habits during the early stages of the COVID-19 outbreak in Spain resulted in a 12% increase in food loss and waste [8]. Furthermore, increased shortages of agricultural and food processing workers caused by illness or fear of becoming ill led to fruit and vegetable crops being destroyed [7], and closures or reduced processing capacity of animal slaughter plants [9–11]. This severely restricted access for market-ready livestock and poultry and resulted in the unfortunate need to humanely euthanize and dispose of millions of animals originally destined to enter the food chain [12,13]. Economic losses due to COVID-19 disruptions have been estimated to be at least USD 13.6 billion for U.S. cattle producers and USD 5 billion for U.S. pork producers, with 30% less meat available to consumers at a projected 20% increase in price [12]. In addition to these economic losses, lack of sufficient rendering capacity for disposal of market-ready animals has required using other less desirable methods of disposal, which are detrimental to the environment and cause inefficiencies in resource use (i.e., land, water, nitrogen, phosphorus, labor) while increasing biosecurity risks [13]. As a result of the COVID-19 pandemic, researchers have proposed rethinking and redefining sustainability as the intersection of the economy, environment, society, and human health [5]. Furthermore, a more holistic approach that includes climate, economics, and nutrition is needed to improve food supply chain efficiency by reducing food loss and improving waste management of food supply chains adversely affected by changes in consumption patterns caused by pandemics [8]. In fact, the European Union has already indicated plans to use knowledge gained from COVID-19 impacts on food supply chains to revise the Farm to Fork subsection of the Green Deal reforms [14]. Now, more than ever before, it is time for researchers and food sector experts to accelerate efforts for developing more sustainable and modern food systems by reducing the cost of food waste recovery and reutilization in the food chain [15]. However, a very important component of food loss that has not been considered in all of these proposals, which also has dramatic effects on food security and sustainability, are mortalities caused by animal disease epidemics.

The African Swine Fever epidemic in China caused estimated losses of 220 to 300 million pigs that were originally destined for the food chain in 2019 [16,17]. This enormous number of pigs represents 25–35% of the total world pig population that died or were depopulated from infected farms [16,17]. Because of the lack of infrastructure to manage the disposition of millions of pigs, the capabilities to recover nutrients from carcasses through rendering was not possible, and carcass burial and disposal in landfills were used at great environmental costs and biosecurity risks [18]. In addition, highly pathogenic avian influenza outbreaks in many countries around the world have resulted in losses of millions of chickens due to mortality and depopulation [19]. Unfortunately, the likelihood of future disruptions in global food animal production caused by animal disease epidemics is increasing because of increased global trade and travel, urbanization, exploitation of natural resources, and changes in land use [20–23].

These unprecedented food losses due to disruptions in global food supply chains have created an urgent need to reevaluate the intertwining of resource recovery, environmental impacts, and biosafety of various food waste streams and animal carcasses to achieve the greatest value. This is essential because animal-derived foods provide about one third of total human protein consumption [24], but their production requires about 75% of arable land [25] and 35% of grain resources, while contributing about 14.5% to total greenhouse gas emissions [26]. Reimagining recovery of nutrients from food

waste and animal carcasses, and subsequent recycling of these valuable nutrients into animal feed, can provide tremendous opportunities to use less arable land and rely less on global grain supplies to produce meat, milk, and eggs, while reducing animal agriculture's contribution to greenhouse gas emissions. Therefore, the purpose of this review is to summarize the current knowledge of the benefits and limitations of recycling various pre-harvest to post-harvest food animal-derived waste sources, as well as retail to post-consumer food waste sources, into animal feeds to achieve greater food security and sustainability during an era of escalating food losses throughout the entire food supply chain.

2. Maximizing Resource Recovery and Value of Waste Streams

2.1. Food Waste

Food waste disposal options have been characterized in a hierarchical order of priority based on achieving the greatest value from resource recovery while minimizing negative impacts on the environment [27]. The best solution and highest priority are to minimize or eliminate food waste, followed by redistributing food to hungry people. The next greatest priority is to convert food waste into animal feed, which is preferable to composting, anaerobic digestion to produce biogas, and disposal in landfills [27]. Food waste has been fed to pigs in every country for centuries, but since 2001 it has been banned in the European Union due to illegal feeding of uncooked food waste, which was associated with the foot-and-mouth disease outbreak in the United Kingdom [28]. Concerns about pathogen transmission as well as an abundant supply of relatively low-cost corn and soybean meal in the United States has also limited feeding food waste to pigs, which has been banned in 18 states [16]. In contrast, Japan (2001), South Korea (1997), and Taiwan (2003) have developed tightly regulated policies and invested in substantial infrastructure using adequate thermal processing to promote the conversion of 35–43% of food waste into animal feed [28].

The wide disparity in government policies among countries regarding recycling of food waste into animal feed has severely limited the ability to reuse the valuable nutrients, reduce negative environmental impacts, and improve sustainability of pig production in the United States and the European Union, which produce much greater quantities of food waste than Japan and South Korea. Furthermore, these Asian countries have demonstrated during the past 20 years that biosafety risks can be adequately managed. Now that social and consumer pressure is increasing to produce food with a lower carbon footprint and conserve resources [29–31], recycling food waste into animal feed needs to be revisited as a viable option in all countries around the world if adequate biosafety processes can be implemented and regulated.

2.2. Carcass Rendering

Options for managing mass carcass disposal vary by country or region, but in the United States an environmental impact statement and guidelines for mass carcass management options during a national health emergency have been developed [32]. Approved options include unlined burial, open-air burial, composting, offsite rendering, landfill, and fixed-facility incineration. Other disposal options that may be considered include alkaline hydrolysis, anaerobic digestion, microwave sterilization, and gasification [32], but these options do not currently provide sufficient capacity to dispose of large numbers of carcasses and are not available in many locations. In the European Union, Animal By-Product Regulations (1069/2009) classify sources and characteristics of animal by-products into one of three categories [33]. Feeding animal by-products to terrestrial animals other than fur animals of the same species, and feeding catering waste to farmed animals is prohibited [33] because of perceived risks of incomplete destruction of pathogens and prions (proteins causing transmissible spongiform encephalopathy) entering the animal feed supply chain [34]. However, approved disposal methods, depending on classification category, include incineration, burial in authorized landfills following processing, composting, and biogas production [33]. Differences in interpretation of relative environmental and biosecurity risks of various carcass disposal options have led to different legal

requirements and regulations in various countries [34]. More information is needed for all carcass disposal methods so that more comprehensive environmental life cycle analyses and biosecurity risk assessments can be conducted to determine the methods that are least detrimental to the environment and biosafety while providing the greatest resource recovery value [34].

3. Comparison of Environmental Impacts of Alternative Disposal Methods

3.1. Food Waste

Although recycling food waste into animal feed is a higher value alternative with fewer negative environmental impacts than composting, anaerobic digestion, and landfill disposal, it is surprising that more comprehensive and comparative studies of disposal methods have not been conducted. A summary of nine published studies that compared the environmental impacts of using food waste as wet or dry animal feed with the alternatives of anaerobic digestion for biogas production, composting, incineration, and landfill is shown in Table 1. In general, results from these studies show greater environmental benefits from using food waste as animal feed compared to the other disposal alternatives, but have mainly focused on estimating impacts on global warming using greenhouse gas (GHG) emissions as indicators, with limited evaluation of impacts on the use of such resources as energy, land, and water. Furthermore, several of these researchers indicated that results obtained under the scope, scenarios, and assumptions used in each study may not apply to broader applications and suggested that more studies are needed using harmonized assessment approaches. Another key finding of these studies was that the nutritional composition of food waste sources affects the extent of GHG reduction. Nutritional composition also determines whether recycling a specific type of food waste into animal feed was the most beneficial option. For example, Eriksson et al. [35] showed that bread waste had the greatest potential for reducing GHG emission, followed by chicken, beef, and bananas, with lettuce having the lowest potential. These results suggest that food waste sources that contain high energy and dry matter content are more suitable for use as animal feed than less nutritionally dense sources.

Table 1. Summary of Life Cycle Assessment studies comparing environmental impacts of food waste disposal options with converting food waste to animal feed.

Food Waste Source/Reference	Disposal Methods Compared	Environmental Indicators	Key Results
Household and catering food waste [36]	Composting Incineration Landfill ¹ Dry animal feed	Global warming Human toxicity Acidification Eutrophication Ecotoxicity	Feed manufacturing had: <ul style="list-style-type: none"> • lowest global warming potential • lowest human toxicity except for incineration • less acidification potential than composting and incineration • highest eutrophication potential • less ecotoxicity than composting
Kitchen and food factory waste [37]	Wet animal feed (sterilization) Dry animal feed Incineration	Global warming Energy consumption Water use	<ul style="list-style-type: none"> • GHG emissions (g CO₂ equivalent/kg DM): • wet feed (268) < incineration (1066) and dry feed (1073) • Energy consumption (MJ/kg DM): • wet feed (3.9) < incineration (14.5) < dry feed (16.7) • Water use (L/kg DM): • wet feed (2.9) < dry feed (5.1) < incineration (1035)
Household and catering food waste [38]	Composting Dry animal feed Wet animal feed Landfill	Global warming	1 tonne of food waste contributed: <ul style="list-style-type: none"> • 61 kg CO₂ equivalent from wet feeding • 123 kg CO₂ equivalent from composting • 200 kg CO₂ equivalent from dry feeding • 1010 kg CO₂ equivalent from landfilling
Household and catering food waste [39]	Anaerobic digestion Composting Dry animal feed Wet animal feed Incineration Landfill	Global warming Energy/resource recovery	Environmental benefit/cost ratio was: <ul style="list-style-type: none"> • 0.42 for wet feeding • 0.26 for dry feeding • 0.26 for dryer incineration • 0.22 for composting • 0.11 for anaerobic digestion • 0.04 for landfilling

Table 1. Cont.

Food Waste Source/Reference	Disposal Methods Compared	Environmental Indicators	Key Results
Catering, retail, and manufacturing food waste [40]	Anaerobic digestion Machine composting Windrow composting Dry animal feed Wet animal feed	Global warming Economics	1 tonne of food waste contributed: <ul style="list-style-type: none"> • −126 kg CO₂ equivalent for dry feeding • −48 kg CO₂ equivalent for anaerobic digestion • −48 kg CO₂ equivalent for wet feeding • +5 kg CO₂ equivalent for windrow composting • +45 kg CO₂ equivalent for machine-integrated composting
Evaluated by-products used in animal feeds including distiller's waste, rapeseed cake, whey permeate, fodder milk, and bakery residues [41]	Anaerobic digestion Anaerobic digestion with portion diverted to animal feed	Global warming	All industrial organic by-products evaluated are suitable for biogas production, provide substantial reduction in GHG compared with fossil fuels, but contribute to eutrophication and acidification potential. If these by-products are used as animal feed, the reduction would be significantly less.
Retail food waste [42]	Anaerobic digestion Dry animal feed (bread) fraction combined with anaerobic digestion of remaining fraction	18 environmental and health impact categories	More environmental benefits were obtained by converting the bread waste portion into animal feed than by using only anaerobic digestion to produce heat and electricity.
Compared banana, chicken, lettuce, beef, bread [35]	Anaerobic digestion Dry animal feed Composting Donations Incineration Landfill	Global warming	<ul style="list-style-type: none"> • Anaerobic digestion and food donations had the greatest effect on reducing GHG emissions, followed by incineration and animal feed • Composting and landfills increased kg CO₂ equivalent/kg • Bread had the greatest benefit for reducing GHG emissions when converted to animal feed, followed by chicken and beef
Household and catering food waste [43]	Anaerobic digestion Composting Dry animal feed Wet animal feed	14 environmental and health impact categories	<ul style="list-style-type: none"> • Wet feed had the highest score for 13/14 impacts • Dry feed had second best score for 12/14 impacts • Overall average ranking of disposal technologies was: <ul style="list-style-type: none"> • 1.1 for wet feed • 2.2 for dry feed • 3.3 for anaerobic digestion • 3.4 for composting

¹ Landfill with and without electricity generation.

3.2. Animal Mortalities and Carcass Residuals

Environmentally sustainable and biosecure disposal of animal carcasses resulting from on-farm mortality or from inedible components of carcasses after slaughter is an important function of food animal production supply chains. Globally, the most common methods for disposal of animal mortalities include burial, burning, incineration, rendering, composting, anaerobic digestion, and alkaline hydrolysis [34]. Some of these disposal methods are prohibited in certain countries because of real and perceived biosafety and environmental risks associated with them [34]. Gwyther et al. [34] conducted a comprehensive review of the socioeconomic, human health, biosecurity, and environmental impacts of various carcass disposal methods and a summary of relative environmental impacts is shown in Table 2. It is unfortunate and somewhat surprising to discover the lack of information for one or more environmental impact indicators for each of these disposal methods. Despite this incomplete environmental impact information for various carcass disposal methods, rendering is considered to have moderate effects on odor and water pollution, good impact on reducing GHG emissions, and very good ranking for impacts on soil and vegetation. Only anaerobic digestion was considered a better alternative than rendering for minimizing odor and GHG emissions. Although various other disposal methods ranked higher than rendering in specific categories, it is important to remember that rendering represents much greater value for resource (nutrient) recovery than all of the other disposal methods, which is important from an environmental sustainability perspective. Gooding and Meeker [44] compared the GHG emissions, resource recovery, and biosecurity differences between using anaerobic digestion, composting, and rendering of animal carcasses. Results from their analysis showed that rendering resulted in at least three times greater economic value than products resulting from anaerobic digestion and at least five times greater value than composting, and concluded that rendering is the most sustainable method for handling large quantities of animal carcasses. Currently, about 85% of rendered animal by-products in the U.S. are used in animal feeds, with the remaining 15% used in biofuels production and other industrial products [44].

4. Potential Amounts of Food Waste Streams That Can Be Used as Animal Feed Ingredients

Globally, about 6 billion tonnes of feed (dry matter basis) is consumed by food-producing animals annually, of which 72% is comprised of roughages consumed by ruminants (i.e., cattle, goats, and sheep) [45]. Of the 1.57 billion tonnes of grain, grain by-products, and oilseed meals consumed, 65% (about 1 billion tonnes) are fed to swine and poultry [45]. To put this in perspective, more than 1.3 billion tonnes of edible food material is wasted annually around the world [2], which is 3 million tonnes more than the global consumption of all cereal grains, by-products, and oilseed meals by swine and poultry combined. In addition, about 60 million tonnes of rendered animal by-products are produced annually from the global meat-processing and animal production industry [46]. Therefore, there is tremendous opportunity to recycle energy and nutrients from various food waste sources into animal feed, especially for swine and poultry because they are unable to efficiently utilize fiber in roughages and require diets that are more energy- and nutrient-dense than those for ruminants. By repurposing a greater proportion of food waste into animal feed, there would be much less pressure on land and water use for agricultural purposes, as well as less dependence on global crop production for animal feed. In fact, zu Ermgassen et al. [28] estimated that if the European Union were to adopt regulated and centralized systems for safely recycling food waste into animal feed, similar to those being used successfully in Japan and South Korea, it would result in a 21.5% reduction in land use (1.8 million hectares) for EU pork production. Furthermore, if 39% of the total amount of food waste in the EU was used in pig feeds, it could replace 8.8 million tonnes of edible grains currently fed to pigs, which is equivalent to 70.3 million tonnes of annual cereal consumption by EU citizens [47]. These conservative estimates do not include the additional benefits from processing and using more rendered animal by-products in animal feed, but they clearly show the enormous potential to improve recovery of energy, nitrogen, and phosphorus by diverting these valuable resources toward feed use in food animal production systems.

Table 2. Summary of relative environmental impacts ¹ of various livestock mortality disposal methods used routinely around the world (adapted from [34]).

Disposal Method	Pollution and Contamination					
	Odor	GHG Emission	Air	Soil and Vegetation	Water	Land Application of Waste
Burial	-	-	Very low	High	Moderate	NA
Burning	Very high	??	??	??	??	??
Incineration, on-farm ^a	Low	High	Low ^b	Low ^b	Low ^b	??
Incineration, large central facility	Very low	High	Moderate ^b	Moderate ^b	Moderate ^b	??
Rendering	Moderate	Low	??	Very low	Moderate	??
Composting ^c	Low	Low	??	Moderate	??	Low
Anaerobic digestion	Low	Very low	Very low	??	??	Low
Alkaline hydrolysis	Moderate	??	??	Low	Moderate	Moderate

¹ Relative impacts are ranked based on Very high, High, Moderate, Low, Very low environmental impacts in each category; ?? = more research is needed due to limited information; NA = not applicable. ^a Assumes use of afterburners. ^b Omits pre-incineration handling and storage of carcasses that may result in biosecurity risks. ^c Assumes unlined static pile with no forced aeration.

5. Urgent Need to Achieve Greater Global Nitrogen, Phosphorus, Carbon Resource Recovery

Food production requires the use of vast amounts of resources, including land, water, energy, fertilizer, and other inputs that contribute to climate change, soil and water degradation, and loss of biodiversity and habitats [48]. Global nitrogen (N), phosphorus (P), carbon (C), and water cycles are the major biogeochemical components required for sustaining life, which were stable, self-sustained, and regularly recycled on various temporal scales on the planet at one time in history, but now these cycles are disrupted [49]. In fact, the planetary boundaries of N and P biogeochemical flows have been exceeded [50] and natural P deposits are becoming depleted.

Food animal production plays a critical role in these global N and P cycles [51] because animal consumption represents more than 80% of the total N and P harvested, but unfortunately only 20% of N and P is converted into edible products for human consumption [52]. Therefore, improving the efficiency of N and P use is essential for achieving global food security and sustainability [52–54]. Recovering and recycling greater amounts of energy and nutrients from food waste and animal carcasses into animal feed will not only improve the efficiency of energy, N, and P use in animal protein production, but also has the potential to simultaneously reduce GHG emissions from food waste disposal in landfills. Using livestock and poultry to recycle these nutrients into animal-derived food products is a prudent and practical strategy for recovering these wasted resources.

5.1. Nitrogen

The consumption of animal-derived foods contributes 18% of calories and 25% of protein to the world human population [55]. Demand for pork and poultry meat is expected to increase with future population growth and rising incomes [55], which will increase demand for feed protein. Currently, there is an insufficient quantity of high protein feed ingredients to support current levels of global animal production, and this deficit will become worse as animal production increases in the future to meet increased consumer demand for meat, milk, and eggs [56].

5.2. Phosphorus

Phosphorus is a critical resource that is essential for achieving global food security in the future [57]. Most of the global phosphate rock is mined for use in food production [58], but it is a finite resource with no substitutes and cannot be produced in greater amounts than what already exist in the Earth's deposits. Estimates of the rate and timeline of when high quality global phosphate reserves will be depleted are highly variable [59–65], but only 20% of the amount of mined P is ultimately consumed as food [59]. As a result, the convergence of the increasing depletion of global P reserves for use in food production and the excessive P losses to aquatic ecosystems, which cause eutrophication in lakes and coastal ecosystems [66,67], requires implementation of more comprehensive practices that prevent P losses and improve the efficiency of P use in food production [68].

6. Most Food Waste and Rendered Animal By-Products Are Concentrated Sources of Energy, Nitrogen, and Phosphorus

6.1. Energy, Protein, and Phosphorus in Animal Nutrition

Swine and poultry require nutritionally dense diets. Energy, protein (amino acids), and phosphorus are the three most expensive components of animal diets [69]. Gross energy (GE) content represents total calories in a feedstuff, and the metabolizable energy (ME) content is an estimate of the proportion of GE retained by the animal after accounting for energy losses from digestion (feces) and metabolism (urine) [69]. The crude protein content of a food or feed ingredient is estimated by determining the nitrogen content and multiplying by a factor of 6.25 [69]. Although the nitrogen content varies among foods, the factor of 6.25 is derived from the assumption that an average of 16 g of nitrogen is present in 100 g of protein [69]. Most plant-based feed ingredients (i.e., grains, grain by-products, oilseed by-products) contain relatively low concentrations of phosphorus, and much of it is present in the

chemical form of phytate, which is indigestible for pigs and poultry [69]. In contrast, animal-derived feed ingredients contain relatively high concentrations of phosphorus that is also highly digestible.

6.2. Nutritional Composition of Food Waste Sources

Several studies have been conducted to determine the energy and nutrient composition of various food waste sources [70], especially for restaurant and cafeteria waste [71,72]. Dou et al. [48] summarized nutrient composition data from several food waste sources and reported that the average crude protein content among sources was moderately high (19.2%), lipid content was very high (21.5%), and crude fiber content was low (6.2%), indicating that many food waste sources are rich sources of energy and protein and suitable for use in swine and poultry diets. Similarly, Truong et al. [73] summarized studies that evaluated the nutritional composition and feeding value of various food waste sources for poultry and concluded that all were suitable for use in broiler and laying hen diets at appropriate diet inclusion rates.

As expected, there is considerable variability in nutrient content among samples within and between food waste sources [48]. Managing variability in nutrient content and digestibility of feed ingredients is one of the greatest challenges in optimizing diet formulations in precision nutrition animal feeding programs [74]. Fung et al. [75,76] reported that using nutrient composition data of some food waste sources in selected energy prediction equations can provide accurate estimates of digestible and metabolizable energy content for swine. Therefore, the development and use of accurate prediction equations to estimate ME and digestible nutrient content are a potential practical solution for managing variability in nutrient content among food waste sources and formulating precision nutrition diets.

Knowing the general proximate analysis of food waste sources is useful, but it is more important to obtain accurate estimates of ME, digestible amino acids, and digestible phosphorus content for accurate diet formulation. Accurate and precise diet formulation is essential for optimizing caloric and nutritional efficiency of animal growth as well as minimizing nutrient excretion in manure. Unfortunately, only a few studies have been conducted to determine the ME, digestible amino acids, and digestible phosphorus content of food waste sources for poultry and swine [73,75,76]. Therefore, additional studies are needed to develop more robust and comprehensive ME and digestible nutrient composition databases of various food waste sources for swine and poultry to encourage animal nutritionists to fully capture the nutritional and economic value of food waste sources when formulating nutritionally adequate and cost-effective complete animal feeds.

Although a few studies have shown nutritional benefits from feeding food waste to ruminants [77–80] and fish [81], most studies have been conducted with poultry and swine (Table 3). All of these studies not only report the nutrient composition of the various food waste sources being evaluated, but also provide information on appropriate diet inclusion rates to achieve optimal growth performance and, in some cases, meat quality, when fed to poultry and swine.

Table 3. Published studies evaluating the nutritional composition and feeding value of various types of food waste in swine and poultry diets.

Food Waste Source	Poultry Feeding Value References	Swine Feeding Value References
Bakery by-product/breakfast cereal	[82–86]	[87–89]
Fish waste	[90]	[76]
Fruit and vegetable waste	[91–94]	[76]
Household waste, dried	[95–97]	[75]
Meat meal	[98]	-
Municipal waste	[99]	[75,100]
Restaurant and cafeteria waste, dried	[101]	[75,102–106]
Supermarket waste	[107]	[75,76]

6.3. Nutritional Efficiency of Food Waste Sources Can be Equivalent or Greater Than Corn and Soybean Meal

Nutritional efficiency can be defined as the proportion of GE and nutrients in a feed ingredient that is digested, absorbed, and used by an animal for productive purposes [69] (i.e., meat, milk, and

egg production). The most nutritionally and economically valuable feed ingredients are those that contain high concentrations of ME, digestible amino acids (nitrogen), and digestible phosphorus [69]. Globally, corn is generally considered to be the reference standard for comparing grain-based energy sources, while soybean meal is used as the standard for comparing protein sources because they are the most widely used and economical energy and protein sources in animal feeds [108]. A comparison of the energy, N, and P efficiency of several food waste sources fed to swine, with corn and soybean meal used as energy and protein standards, is shown in Table 4. Except for food waste from the transfer station and fruit and vegetable waste, all other food waste sources contained more ME than corn and soybean meal and had comparable ME:GE content. The amount (g/kg DM) of digestible N in fish waste exceeded that in corn and soybean meal, whereas supermarket waste contained about four times the amount in corn, but less than soybean meal. Lastly, the digestible P contents (g/kg dry matter) in fish (17.4), supermarket (3.0), and fruit and vegetable (2.0) wastes were greater than in corn (0.99), and fish waste exceeded the digestible N content of soybean meal. Furthermore, fish, supermarket, and fruit and vegetable wastes far exceeded the digestible P content in corn, and contained 460%, 80%, and 53%, respectively, of the digestible P content of soybean meal. These results clearly show that the nutritional value of using common food waste sources in swine diets can have a significant impact on recycling and conserving energy, nitrogen, and phosphorus resources while minimizing the dependence on corn and soybean meal as feed ingredients in swine and poultry diets.

Table 4. Gross energy (GE), metabolizable energy (ME), and crude protein (CP) and phosphorus (P) content and digestibility of food waste sources compared with corn and dehulled soybean meal for swine (dry matter basis).

Ingredient	GE, kcal/kg	ME ¹ , kcal/kg	ME:GE	CP ² , %	Digestible N ³ , g/kg	P ⁴ , %	Digestible P ⁵ , g/kg
Corn ^a	4454	3844	0.86	9.33 (80)	11.9	0.29 (34)	0.99
Dehulled soybean meal ^b	4730	3660	0.77	53.05 (87)	73.8	0.79 (48)	3.79
Food waste source							
Supermarket ^c	5909	4832	0.82	25.51	-	0.64	-
University dining hall ^c	5419	4188	0.77	18.90	-	0.30	-
Transfer station ^c	4829	3198	0.66	17.71	-	0.46	-
Household source separated organics ^c	4455	4114	0.92	13.53	-	0.31	-
Fish waste ^d	6376	4820	0.76	62.49 (95)	95.0	2.95 (59)	17.4
Supermarket ^d	6316	4922	0.78	29.42 (89)	41.9	0.37 (82)	3.03
Fruit and vegetable ^d	4123	2460	0.60	10.13 (11)	1.78	0.27 (74)	2.00

¹ Metabolizable energy was calculated based on prediction equation from [109]. ² Values in parentheses are standardized ileal digestibility (%) [76]. ³ Digestible nitrogen (N) was calculated by assuming crude protein = nitrogen content \times 6.25, multiplying by the digestibility coefficient for each ingredient and converting to a g/kg of dry matter basis. ⁴ Values in parentheses are standardized total tract digestibility (%) [76]. ⁵ Digestible phosphorus (P) was calculated by multiplying total P content by the respective digestibility coefficient for each ingredient and converting to a g/kg of dry matter basis. ^a Corn was used as a standard of reference because it is the predominant grain and energy source used in animal feeds globally due to its high ME:GE content, compared with other cereal grains. Values were obtained from [69]. ^b Soybean meal was used as a standard of reference because it is the predominant protein source used in animal feeds globally due to its high crude protein content, digestibility, and desirable amino acid profile, compared with other high protein ingredients. ^c Values obtained from [75]. ^d Values obtained from [76].

6.4. Nutrition and Technical Challenges Limiting Use of Food Waste in Animal Feed

Although it is clear that many food waste streams are rich sources of energy as well as of digestible nitrogen and phosphorus, and can serve a valuable function in conserving resources and reducing environmental impacts, there are several nutritional and technical limitations that need to be addressed to optimize their use in animal feeds. Nutritional challenges include (1) managing variability in energy and nutrient content and digestibility within and among sources, (2) accurate ME, digestible amino acid, and digestible phosphorus content of food waste sources being fed so that the amount of

supplementation of other ingredients and additives to formulate nutritionally balanced diets can be determined, and (3) potential feed and food biosafety risks, including bacterial and viral pathogens, parasites, and prions associated with transmissible spongiform encephalopathies (TSEs).

Along with these nutritional challenges, there are also technical challenges for utilizing food waste as animal feed. Depending on the source, seasonality and other reasons for inconsistent supplies may occur that may require storage capabilities. Handling characteristics (bulkiness, moisture content, powdery texture), and the need for further processing such as grinding, drying, and thermal treatment for pathogen inactivation, require use of specialized equipment. Finally, except for countries like Japan and South Korea, most countries lack infrastructure, except for rendering, which has limited the development of recycling food waste into animal feed.

6.5. Nutritional Efficiency of Rendered Animal By-Products Can be Equivalent or Greater Than Corn and Soybean Meal

Similar to some of the food waste sources described in Table 4, some rendered animal protein by-products such as blood meal, chicken by-product meal, and feather meal contain greater ME content for swine than corn and soybean meal (Table 5). Furthermore, the ME:GE of blood meal, chicken meal, and chicken by-product meal is comparable to soybean meal, indicating that similar caloric efficiency can be achieved by using rendered animal by-products as partial replacements for corn and soybean meal in swine diets. In addition, all animal protein by-products listed in Table 5, except for poultry meal, contain substantially more digestible N content than soybean meal, with blood meal containing more than twice the amount of digestible N as soybean meal. Digestible P is also three to five times greater in many rendered animal protein by-products (except for blood meal and feather meal), compared to soybean meal, and they contain even greater amounts than the digestible P content in corn. Although the chemical composition and digestibility varies within and among sources, digestible and metabolizable energy can be accurately predicted for pigs using specific nutritional components, which is essential when accurately formulating diets in precision swine feeding programs [110]. Therefore, using any of the food waste and rendered animal protein by-products as complete or partial replacements for corn and soybean meal in swine diets could dramatically reduce dependence on corn and soybean meal use in swine diets and other animal feeds, and reduce land and water use while conserving N and P resources.

Table 5. Gross energy (GE), metabolizable energy (ME), and crude protein (CP) and phosphorus (P) content and digestibility of rendered animal protein by-products compared with corn and dehulled soybean meal for swine (dry matter basis).

Ingredient	GE, kcal/kg	ME, kcal/kg	ME:GE	CP, %	Digestible N ³ , g/kg	P, %	Digestible P ⁴ , g/kg
Corn ¹	4454	3844	0.86	9.33 (65)	9.70	0.29 (26)	0.75
Dehulled soybean meal ¹	4730	3660	0.77	53.05 (82)	69.6	0.79 (39)	3.08
Animal protein by-product²							
Blood meal	5789	4618	0.80	97.09 (93)	144	0.20 (99)	1.98
Chicken meal	5015	3719	0.74	69.52 (91)	101	3.26 (42)	13.7
Chicken by-product meal	5521	4204	0.76	69.20 (87)	96.3	1.84 (63)	11.6
Feather meal	5809	4031	0.69	88.86 (80)	114	0.32 (59)	1.89
Meat meal	4732	3034	0.64	57.97 (81)	75.1	3.49 (38)	13.6
Meat and bone meal	4469	2620	0.59	56.14 (82)	73.7	4.46 (33)	14.7
Poultry meal	4183	2508	0.60	49.26 (80)	63.1	4.51 (37)	16.7
Poultry by-product meal	4,381	3,038	0.69	58.04 (87)	80.7	4.67 (34)	15.9

¹ Values were obtained from [69]. Values in parentheses for CP and P are apparent digestibility values (%). ² Values were obtained from [110]. Values in parentheses for CP and P are apparent digestibility values (%). ³ Digestible nitrogen (N) was calculated by assuming crude protein = nitrogen content × 6.25, multiplying by the digestibility coefficient for each ingredient and converting to a g/kg of dry matter basis. ⁴ Digestible phosphorus (P) was calculated by multiplying total P content by the respective digestibility coefficient for each ingredient and converting to a g/kg of dry matter basis.

7. Using Food Waste and Rendered Animal By-Products as Animal Feed Ingredients Can Substantially Reduce Several Environmental Impacts of Food Animal Production

Global food animal production contributes about 14.5% (7.1 gigatonnes of CO₂ equivalent) of the total human-induced GHG emissions per year, with the greatest proportion from beef (35.3%) and dairy cattle (30.1%), followed by swine (9.5%) and poultry (8.7%) [26]. Of the total GHG emissions attributed to global food animal production, about 46.7% is associated with the production, processing, and transport of feed, followed by about 39.1% attributed to enteric methane emissions from ruminants, with about 9.5% attributed to methane and N₂O emissions from manure storage [26]. Because feed production, processing, and transport represent the greatest proportion of GHG emissions in all food animal sectors, the greatest opportunity to significantly reduce GHG emissions is represented by using feed ingredients that have less environmental impact.

Historically, decisions on feed ingredient selection and use were determined almost exclusively on price and the economics of animal production (i.e., feed cost/kg of body weight gain, margin over feed cost) [111,112]. Although the economic value of feed ingredients will always be the primary consideration when selecting feed ingredients, consideration for their contribution toward reducing the environmental impacts of animal production is a rapidly emerging trend in the global feed and food animal production industries [113]. This has led to the development of life cycle assessment (LCA) databases of feed ingredients to use in developing “eco-nutrition” feeding programs.

Life cycle assessment of environmental impacts of food production systems has become a widely accepted reference method for guiding decisions and transitioning toward more globally sustainable production and consumption patterns [114]. However, although methodology for LCA has been standardized and guidelines have been published for evaluating environmental performance of animal feed supply chains (101), LCAs have some limitations [115,116].

A limited number of databases of feed ingredients with LCA indicator estimates have been developed and generally only include types of ingredients that are approved for use in the European Union. Because of regulatory restrictions on the use of food waste and rendered animal by-products in animal feeds in the EU, LCA estimates are either absent or limited to only a few by-products. The largest LCA database (962 feed ingredients) with the most LCA indicators ($n = 18$) and the greatest global application (EU, U.S., Canada) was developed by the Global Feed LCA Institute (GFLI) (<https://tools.blonkconsultants.nl/tool/16/>). However, it has estimates only for spray dried blood meal, animal protein meals, and animal fats derived from beef, pigs, and poultry with no other food waste sources. Although the animal by-products described in this database are somewhat generic, they do provide a general basis for comparing rendered animal protein by-products with various other feed ingredients using the 18 environmental impact indicators. For example, in comparison with Brazilian soybean meal, using these animal protein meals in animal feed would have less impact on global warming, including land-use change, land use, human carcinogenic and non-carcinogenic toxicity, terrestrial ecotoxicity, human health and terrestrial ecosystem effects from ozone formation, mineral resource scarcity, freshwater eutrophication, and marine eutrophication.

In contrast, the Feed Print database [117] includes 274 feed ingredients used under conditions in the Netherlands, and include LCA estimates of only seven environmental indicators for three sources of food waste (ground biscuits, bakery meal, and potato crisps; Figure 1) and four sources of rendered by-products (meat meal, meat and bone meal, hydrolyzed feather meal, and spray dried blood meal; Figure 2). Users of this database specify the level of calculations (supplier of milk products and compound feeds from a feed mill, supplier of by-products and roughage without a feed mill, or farm production including downstream emissions on farm). In addition, the method of land-use change allocation (area-specific or crop-specific) and the allocation method (economic, mass balance, or gross energy) used for the production of feed is specified. The LCA values presented in Figures 1 and 2 are based on calculations for a supplier of by-products without a feed mill, crop-specific land-use change allocation, and the economic allocation method for the production of feed. With the exception of meat meal, all other food waste and rendered animal by-products have less environmental impact on

climate change with land-use change; marine, freshwater, and terrestrial eutrophication; acidification; mineral, fossil fuel, and renewable resource depletion; and land surface use than corn and soybean meal. Therefore, despite the limited LCA data available, using most sources of food wastes and common types of rendered animal by-products as partial or complete replacements for corn and soybean meal can dramatically reduce multiple environmental impacts and provide significant advantages as the global feed and food animal production industries begin implementing eco-nutrition feeding programs. However, much research is needed to expand the list of food wastes and rendered animal by-products in global LCA feed ingredient databases.

8. Real and Perceived Biosafety Risks of Rendered Animal By-Products and Food Waste

Biosafety of feed ingredients and biosecurity of feed supply chains have been an important part of feed ingredient sourcing and feed manufacturing for many decades. The feed industry plays an important role in minimizing the risk of transmission of prions, parasites, bacteria, and viruses from feed to animals and, in some cases, from animals to human food. The risk of transmission of hazardous biological agents is one of the main reasons that food waste and rendered animal by-products have not been used to their fullest potential in animal feeds around the world. Despite global access to all published research information on feed safety risks, some countries like Japan and South Korea have regulations and processes in place to minimize the risk of disease transmission and promote the use of food waste in animal feeds, while other regions like the European Union have regulations that are very restrictive and reflect a different perception of feed safety risks of using food waste and rendered animal by-products in animal feed. It seems that now is an appropriate time to reevaluate the potential biosafety risks and determine if the utilization of these abundant and underutilized food waste and rendered animal by-product nutritional resources can be increased in animal feeds by improving biosecurity process controls, managing critical biosafety risk factors, and overcoming unwarranted feed safety concerns. This process begins with a review of biosafety risks of various food waste and carcass disposal methods.

8.1. Comparison of Biosafety Risks of Carcass Disposal Methods

Prevention of transmission of disease-causing biological agents to animals and humans is an essential consideration when determining the most appropriate disposal method for food waste and animal carcasses. Unfortunately, no reviews have been published to compare the biosafety risks of various food waste disposal methods, but Gwyther et al. [34] conducted a comprehensive review of the socioeconomic, human health, biosecurity, and environmental impacts of various carcass disposal methods, which have relevance to animal-derived food waste sources. As shown in Table 6, there is limited research information available to completely assess the benefits and limitations of various carcass disposal methods for biosecurity, but based on this summary, the most effective carcass disposal methods for preventing transmission of pathogens and prions (biological agents in ruminant animal tissues associated with TSE) are the use of on-farm incineration and alkaline hydrolysis.

Unfortunately, the use of incineration and alkaline hydrolysis methods for disposal of large amounts of animal carcasses is infeasible, particularly during disease epidemics when millions of animal mortalities require immediate disposal. Rendering, composting, anaerobic digestion, and burial methods are more appropriate for handling large volumes of animal mortalities than incineration and alkaline hydrolysis. Optimal carcass disposal should be based on multiple criteria using a holistic assessment of economics, value and extent of resource recovery, biosecurity and risk of disease transmission, and environmental impacts. The Food and Agriculture Organization of the United Nations has suggested that restricting the use of rendered animal by-products in animal feed may result in severe economic and environmental problems, and facilitate disease spread to animals and humans and loss of valuable nutrients [118]. Furthermore, according to Hamilton [46], the United Kingdom Department of Health reported a relative comparison of the potential human health risks from carcass disposal using rendering, incineration, landfill, pyre, and burial, and noted that rendering had minimal impact on every health hazard except prions associated with TSE (Table 7).

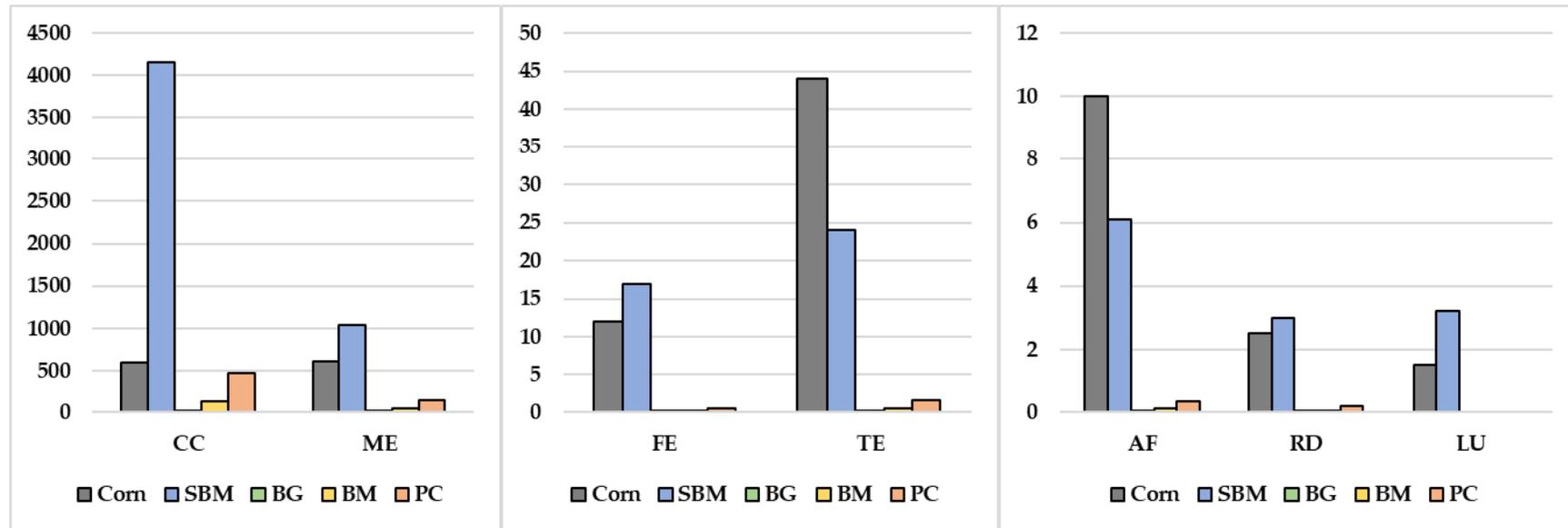


Figure 1. Comparison of environmental impacts of climate change with land-use change potential (CC, g CO₂ equivalent/kg); marine eutrophication potential (ME, mg N equivalent/kg); freshwater eutrophication potential (FE, mg P equivalent/kg); terrestrial eutrophication (TE, mmol N equivalent/kg); acidification (AF, mmol H⁺ equivalent/kg); mineral, fossil fuel, and renewable resource depletion potential (RD, mg SB equivalent/kg); and land surface use (LU, m²/kg) for corn, soybean meal (SBM), ground biscuits (BG), bread meal (BM), and potato crisps (PC) from the FeedPrint LCA ingredient database [118]. The LCA values are based on calculations for a supplier of by-products without a feed mill, crop-specific land-use change allocation, and the economic allocation method for the production of feed.

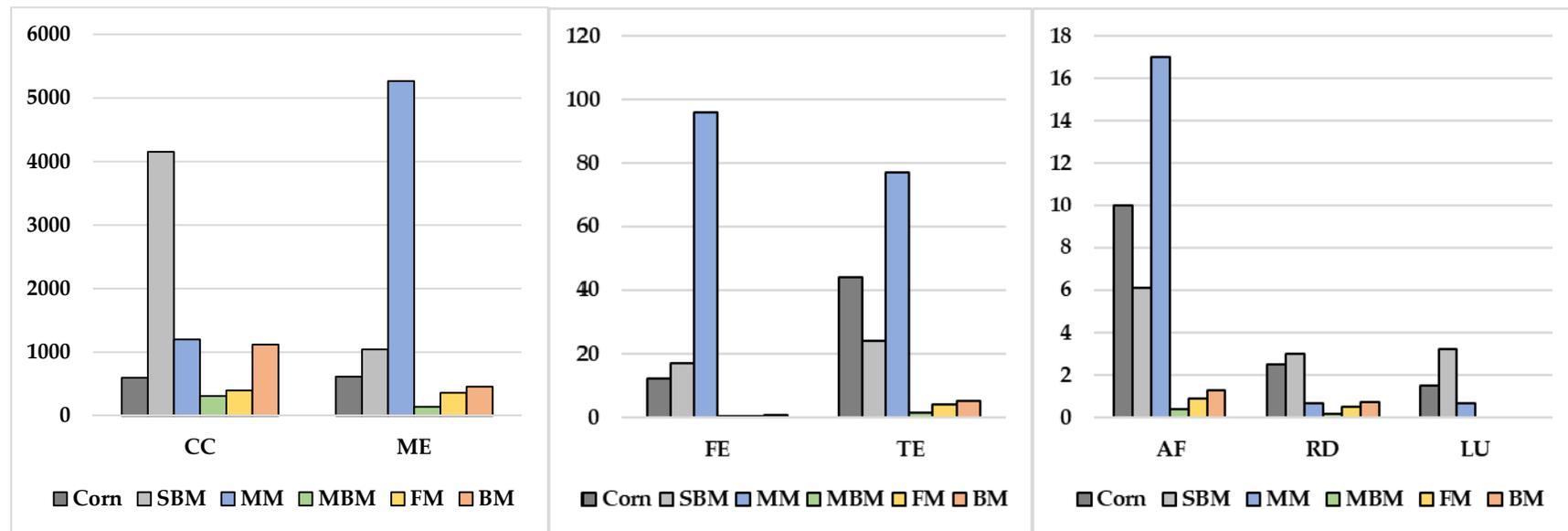


Figure 2. Comparison of environmental impacts of climate change with land-use change potential (CC, g CO₂ equivalent/kg); marine eutrophication potential (ME, mg N equivalent/kg); freshwater eutrophication potential (FE, mg P equivalent/kg); terrestrial eutrophication (TE, mmol N equivalent/kg); acidification (AF, mmol H⁺ equivalent/kg); mineral, fossil fuel, and renewable resource depletion potential (RD, mg SB equivalent/kg); and land surface use (LU, m²/kg) for corn, soybean meal (SBM), meat meal (MM), meat and bone meal (MBM), feather meal (FM), and blood meal (BM) from the FeedPrint LCA ingredient database [118]. The LCA values are based on calculations for a supplier of by-products without a feed mill, crop-specific land-use change allocation, and the economic allocation method for the production of feed.

Table 6. Summary of relative biosecurity risks¹ of various livestock mortality disposal methods routinely used around the world (adapted from [34]).

Disposal Method	Human Health		Pathogen Contamination				
	Dioxins/Furans	Air	Soil and Vegetation	Water	Land Application of Waste	Transport of Animals Off-Farm	Prion Destruction
Burial	Very low	Low	Moderate	??	NA	Very low	Very high
Burning	High	??	??	??	??	Very low	Moderate
Incineration, on-farm ^a	Low	Very low ^b	Very low ^b	Very low ^b	??	Very low	Very low
Incineration, large central facility	Moderate	Very low ^b	Very low ^b	Very low ^b	??	Very high	Very low
Rendering	??	Very low	NA	??	NA	Very high	Low
Composting ^c	??	Moderate	Moderate	??	??	Very low	Moderate
Anaerobic digestion	??	Low	Moderate	Moderate	??	Very low	High
Alkaline hydrolysis	??	Very low	Very low	Very low	Very low	Very low	Very low

¹ Relative impacts are ranked based on Very high, High, Moderate, Low, Very low environmental impacts in each category; ?? = more research is needed due to limited information; NA = not applicable. ^a Assumes use of afterburners. ^b Omits pre-incineration handling and storage of carcasses that may result in biosecurity risks. ^c Assumes unlined static pile with no forced aeration.

Table 7. Summary of potential health risks of various animal carcass and tissue disposal methods (adapted from [46]).

Hazardous Agent	Rendering	Incineration	Landfill	Pyre	Burial
<i>Campylobacter, Escherichia coli, Listeria, Salmonella, Bacillus anthracis, Clostridium botulinum, Leptospira, Mycobacterium tuberculosis var bovis, Yersinia</i>	Low	Low	Some	Low	High
<i>Cryptosporidium, Giardia</i>	Low	Low	Some	Low	High
<i>Clostridium tetani</i>	Low	Low	Some	Low	High
Prions for transmissible spongiform encephalopathies	Some	Low	Some	Some	High
Methane, Carbon dioxide	Low	Low	Some	Low	High
Fuel-specific chemicals, Metal salts	Low	Low	Low	High	Low
Particulates, sulfur dioxide, nitrous oxide, nitrous particles	Low	Some	Low	High	Low
Polycyclic aromatic hydrocarbons, Dioxins	Low	Some	Low	High	Low
Disinfectants, Detergents	Low	Low	Some	Some	High
Hydrogen sulfide	Low	Low	Some	Low	High
Radiation	Low	Some	Low	Some	Some

Gooding and Meeker [44] compared differences in biosecurity, greenhouse gas emissions, resource recovery, and environmental regulations from using anaerobic digestion, composting, and rendering processes to dispose of large quantities of animal carcasses. Results of their analysis showed that the economic value of rendered by-products was at least three times greater than if carcasses were processed using anaerobic digestion, and at least five times greater than if carcasses were composted. Using estimates of the carbon footprint of the rendering process [119], rendering contributed the least amount to total greenhouse gas emissions (CO₂ equivalent) from processing 1000 kg of carcass by-products, where 2500–4000 kg CO₂ equivalent was produced from composting, 60–500 kg CO₂ equivalent was generated from anaerobic digestion, and only 200 kg CO₂ equivalents were produced from rendering [44]. Furthermore, rendering has less biosecurity risk compared with composting, where rendering has been shown to reduce prion infectivity by two logs [120], while composting does not destroy prions, spore-forming bacteria, and other pathogens [121,122]. More research is needed to determine if the use of anaerobic digesters is adequate for destroying prions and pathogens in carcass materials [123]. Despite limited information on the biosecurity of various carcass disposal methods, rendering has many advantages over all other methods, especially for biosecurity, impacts on climate change, economics, and the potential for effectively managing large volumes of animal carcasses resulting from the COVID-19 pandemic and African Swine Fever epidemic.

8.2. Potential Biosafety Risks of Feeding Rendered Animal By-Products to Food-Producing Animals

Historically, the two main biosafety concerns involving feeding rendered animal by-products to food-producing animals are the risks of transmission of *Salmonella* and TSEs, especially bovine spongiform encephalopathy (BSE) [46]. However, in recent years widespread animal disease epidemics such as Porcine Epidemic Diarrhea Virus (PEDV) and African Swine Fever Virus (ASFV) have caused increased scrutiny of biosecurity risks of animal disease transmission through animal-derived feed ingredients and led to their restricted use or elimination in some swine diets [124]. The ultimate determination of the biosafety of feeding rendered animal by-products to animals is primarily dependent on the capability of the thermal treatment conditions used during the rendering process to inactivate pathogenic bacteria, viruses, parasites, and prions.

8.2.1. Adequate Thermal Processing Minimizes Feed Safety Risks of Rendered Animal By-Products

In the United States, dry rendering is the most common process used in either batch or continuous systems, where heat (120 °C to 135 °C) produced by steam condensation is applied and uniformly distributed to ground carcass material for 45 min to 1.5 h under pressure (2.8–4.2 bar), while wet rendering uses high pressure and 140 °C [125]. Gwyther et al. [34] indicated that the European Union requires that for carcasses at high risk for BSE, rendering must be done under processing conditions of 133 °C for 20 min at 300 kPa or equivalent. When comparing these thermal processing conditions used in the rendering process with the temperature and time required to inactivate various prions, parasites, and pathogenic bacteria and viruses in animal tissue matrices (Table 8), it is clear that these hazardous biological agents are destroyed and are no longer infective, except for prions associated with TSE in mammals.

Table 8. Time and temperature to inactivate disease-causing biological agents (prions, parasites, bacteria, and viruses) in animal tissue matrices.

Biological Agent	Temperature and Time for Inactivation	Reference
Prions		
Bovine spongiform encephalitis	136–138 °C for 18 min at 2 bar (29.4 psi)	[125]
Parasites		
<i>Trichinella spiralis</i>	55 °C for 6 min 60 °C for 2 min	[126]
<i>Toxoplasma gondii</i>	60 °C for 1 min	[127]
Bacteria		
<i>Salmonella</i>	80 °C for 30 min	[128]
<i>Escherichia coli</i>	65 °C for 20 min	[128]
Viruses		
African swine fever virus	56 °C for 70 min or 60 °C for 20 min	[129]
Classical swine fever virus	65.5 °C for 30 min or 71 °C for 1 min	[129]
Highly pathogenic avian influenza virus H5 and H7	74 °C for 3.5 s	[129]
Newcastle disease virus	56 °C for 3 h or 60 °C for 30 min	[129]
Foot-and-mouth disease virus	70 °C for 30 min	[129]

Although increasing the time, temperature, and pressure necessary to completely inactivate prions and their infectivity seems possible, it is unclear why this approach has not been adopted in the rendering industry, other than perhaps because of an increase in cost, reduced throughput, and potential loss of some nutritional value of by-products. In fact, Taylor [130] reported that prions are completely inactivated when rendered materials are subjected to 132 °C for 4.5 h at 3 bar (45 psi).

8.2.2. Salmonella

For many decades, *Salmonella* has been one of the most important pathogens to manage in feed ingredients [131,132] and has served as an example of the interrelationships between animal feed safety, food animal production, food processing, public health, and global trade. The first documented evidence of bacterial contamination in the U.S. was in 1948 when *Salmonella* was detected in poultry feed [133]. Since then, numerous studies have documented the presence of *Salmonella* in contaminated feeds around the world [134]. Because feed ingredients can be a potential source of *Salmonella* infection in food-producing animals, regulations to control contamination in feed have existed for many decades in some countries [135]. However, despite many years of research involving factors causing contamination and mitigation strategies to inactivate and control *Salmonella* in feed supply and manufacturing chains, it continues to be a challenge to achieving a *Salmonella* negative standard for animal feeds [135]. Although microbial contamination has been shown in many types of feed ingredients and animal feeds, animal by-product meals have generally been considered to be at highest risk [136].

Concerns about the presence of *Salmonella* in rendered animal by-products (fats and proteins) have played a historic role in government regulations and use of animal by-products in animal feeds in many countries. Beginning as early as 1958, multiple studies have shown that many different serotypes of *Salmonella* were identified in feeds containing animal by-products [137–141]. This subsequently led to applying preventative controls based on Hazard Analysis and Critical Control Point principles to the manufacturing process [142]. However, published surveys from several different countries and time periods show that *Salmonella* contamination can occur not only in animal protein by-products, but also in grains, fish meal, and plant protein sources (Table 9).

Table 9. Summary of surveys reporting percentage of samples contaminated with *Salmonella* in various types of feed ingredients.

Country	Animal Proteins	Plant Proteins	Grains	Fishmeal	Reference
Canada	20	18	5	22	[143]
Germany	6	26	3	-	[144]
Netherlands	6	3	-	-	[145]
United Kingdom	3	7	1	22	[146]
United States	33	10	0	10	[147]

Furthermore, although *Salmonella*-contaminated feed is one of many risk factors for introduction on swine farms, non-feed sources represent much greater risk [135]. In fact, results from field trials have shown that raw materials contaminated with foodborne pathogens, including *Salmonella* spp., *Listeria monocytogenes*, *Campylobacter jejuni*, and *Clostridium perfringens*, were inactivated using the time and temperature conditions employed during the rendering process (Table 10) [148]. Davies and Funk [149] reported that there is a general perception that animal-derived by-products pose the greatest risk of *Salmonella* contamination, but plant-based ingredients can also be contaminated with *Salmonella*. Fortunately, *Salmonella* can be easily inactivated by processing ingredients at 55 °C for 1 h or at 60 °C for 15–20 min [143].

Table 10. Effectiveness of the rendering process to inactivate pathogenic bacteria (adapted from [148]).

Pathogen	Percentage of Positive Samples ^a , %	
	Unprocessed Raw Material	Rendered Final Product
<i>Campylobacter jejuni</i>	20.0	0
<i>Campylobacter</i> spp.	29.8	0
<i>Clostridium perfringens</i>	71.4	0
<i>Listeria monocytogenes</i>	8.3	0
<i>Listeria</i> spp.	76.2	0
<i>Salmonella</i> spp.	84.5	0

^a Samples were collected from 17 different rendering facilities in the United States during summer and winter seasons.

8.2.3. Bovine Spongiform Encephalitis

The risk of bovine spongiform encephalitis (BSE) transmission through ruminant-derived feed ingredients has had dramatic effects on limiting the use of rendered animal by-products and food waste sources containing animal tissues in the global feed industry. Bovine spongiform encephalopathy is part of a group of TSEs that are fatal degenerative diseases of the brain in adult cattle caused by consuming prions (an abnormal form of prion protein attached to the surface of nerve cells) from ruminant by-products such as meat and bone meal containing nervous tissue derived from infected animals [150–152].

The first case of BSE occurred in the United Kingdom in 1985, and it was widely accepted to have resulted from feeding meat and bone meal of ruminant origin to cattle [153]. Shortly thereafter, the European Union implemented regulations that prohibited the feeding of animal protein by-products to all food-producing animals, despite no evidence indicating that pigs can be infected with TSE through the consumption of infected ruminant-derived meat and bone meal [154], and no evidence that BSE can be transmitted between pigs if they were fed brain tissue from cattle [155]. Furthermore, Cutlip et al. [156] conducted a study to determine if feeding rendered meat and bone meal and tallow from scrapie-infected sheep would cause BSE in cattle during a one- to eight-year feeding period. No clinical signs, lesions, or presence of prion protein were detected in the spinal cords and brains of

calves fed rendered meat and bone meal and tallow at maximum recommended diet inclusion rates in this study [156]. However, despite these favorable results, the perception of risk of BSE transmission through animal by-products has led to government regulations and restrictions regarding the use of animal by-products in various countries today [157].

The presence of BSE is geographically limited to the European Union, United Kingdom, and North America [158–160]. Although a case of BSE in cattle was previously reported in Japan, it was assumed to have been caused by feeding contaminated meat and bone meal imported from the European Union [161]. The United States prohibits the feeding of ruminant-derived rendered animal protein by-products to ruminants, while allowing the feeding of these ruminant-derived by-products to swine and poultry. Australia and New Zealand do not have TSEs but allow using ruminant-derived protein meals in some monogastric animal feeds by controlling ingredient imports, enforcing strict feeding regulations, and using proactive surveillance methods [162].

8.2.4. Swine Corona Viruses

More recently, additional skepticism about the biosafety of animal-derived by-products, especially those of porcine origin, relative to the risk of transboundary transmission of foreign animal disease viruses, has limited the use of animal protein by-products in swine diets in North America. Swine diseases of major concern for transboundary transmission include ASFV, PEDV, Classical Swine Fever, foot-and-mouth disease (FMD), and porcine reproductive and respiratory syndrome (PRRS) viruses because they have spread across country borders [163]. The PEDV outbreak that occurred in North America in 2013 and 2014 created initial concerns regarding transmission of viral pathogens through feed, especially animal protein by-products such as spray dried porcine plasma (SDPP). Although it was initially suspected that PEDV was introduced to a swine farm from a common feed source containing contaminated SDPP [164–168], the definitive source and route of PEDV introduction into Canada or the United States has not been determined [169]. However, because of the high swine mortality and economic losses [170] caused by the PEDV epidemic, the use of SDPP and other porcine-derived by-products in weaned pig diets was significantly reduced because they were perceived as high risk for PEDV transmission. As a result of the PEDV epidemic, several studies were immediately conducted to evaluate survival of PEDV and two other corona viruses, Porcine Delta Coronavirus (PDCoV) and Transmissible Gastroenteritis virus (TGEV), in various feed ingredients if they are contaminated [171]. No differences were observed in the number of days to reduce PEDV concentration by one log (delta value) among animal protein by-products (spray dried porcine plasma, blood meal, meat meal, and meat and bone meal), nor were there differences in delta values between these animal protein by-products and plant-based ingredients (i.e., corn, soybean meal, and corn-dried distillers grains with solubles; Table 11). Furthermore, the number of days to achieve a one log reduction of PDCoV and TGEV were much greater for soybean meal than for all animal protein by-products. Results from this study clearly showed that survival of PEDV is not different among animal protein by-products and common plant-based ingredients, and more strikingly, corn and soybean meal are greater risks to PDCoV and TGEV survival than animal-based feeding ingredients if they are contaminated.

8.2.5. African Swine Fever Virus

The continual spreading of the ASFV outbreak in Eastern Europe, China, and other major swine-producing countries in Southeast Asia has become a major threat to global pork production and food security [172]. Although there are no published data showing natural contamination of ASFV in complete feed and feed ingredients, if certain ingredients such as soybean meal or choline chloride were to be contaminated with ASFV, the virus has been shown to survive and be infective under the time and environmental conditions of trans-Pacific and trans-Atlantic shipping models [173]. The USDA-APHIS conducted a qualitative assessment of the likelihood of the ASFV virus entering the United States from legal and illegal transboundary movements of potentially infected animals and contaminated products from ASFV-affected countries or regions [174]. This assessment suggested that feed ingredients

of either animal or plant origin were associated with moderate likelihood for ASFV entry, but with high uncertainty due to lack of data on virus survival throughout the supply chain necessary to cause infection if contaminated. These results suggest that due to lack of data, risk of ASFV transmission was considered similar between rendered animal by-products and plant-based ingredients [174].

Table 11. Comparison of days necessary to reduce Porcine Epidemic Diarrhea Virus (PEDV), Porcine Delta Coronavirus (PDCoV), and Transmissible Gastroenteritis Virus (TGEV) concentration by one log (delta value) in complete feed and various feed ingredients (adapted from [171]).

Feed Ingredient	PEDV	PDCoV	TGEV
Spray dried porcine plasma	1.14	3.25 ^a	19.18 ^a
Blood meal	2.84	1.23 ^a	2.15 ^a
Meat meal	3.87	2.82 ^a	1.04 ^a
Meat and bone meal	4.90	6.22 ^a	0.99 ^a
Corn	2.25	25.60 ^b	11.78 ^a
Soybean meal	7.50	42.04 ^c	41.94 ^b
Low oil DDGS ¹	0.70	6.23 ^a	1.04 ^a
Medium oil DDGS	7.32	3.76 ^a	1.66 ^a
High oil DDGS	0.56	8.80 ^a	0.78 ^a
Complete feed	1.12	2.29 ^a	3.20 ^a

¹ DDGS = dried distillers grains with solubles. ^{a,b,c} Means with uncommon superscripts differ ($p < 0.05$).

8.3. Different Perspectives of Potential Biosafety Risks of Recycling Food Waste into Animal Feed

Historically, various forms of uncooked (“garbage”) or cooked (“swill”) food waste have been fed to livestock, especially swine, in many countries for many centuries [175]. However, during the past few decades, specific disease outbreaks have occurred in a few countries that resulted in different biosecurity perspectives and regulations among countries for recycling food waste into animal feed. Countries such as Japan, South Korea, Taiwan, and Thailand have proactively embraced the nutritional and environmental benefits of recycling a high proportion of food waste into animal feed by developing appropriate regulations and infrastructure to accomplish this while minimizing biosafety risks [176]. In Japan, initial government regulations were implemented in 2001, and were later revised in 2007, that prioritize recycling of food waste into animal feed, compared with other disposal options [40]. In fact, about 40% of food waste in Japan from pre-consumer sources (food manufacturing facilities, wholesale, and retail grocery stores) along with lesser amounts from post-consumer sources (restaurants, households) is thermally processed, recycled into animal feed, and trademarked as “EcoFeed” [177]. Similarly, South Korea has implemented regulations, infrastructure, and processes to convert a high proportion of food waste into safe animal feed. Disposal of food waste in landfills was banned in South Korea in 2005 [48], and about 45% is recycled into animal feed, 45% is composted, and the remaining 10% is disposed through anaerobic digestion, vermicomposting, and co-digestion with sewage sludge [39]. Both Japan and South Korea have demonstrated that recycling a large proportion of domestic food waste into animal feed can be successfully accomplished by developing and implementing appropriate regulations and oversight to ensure adequate thermal treatment, storage, and transport of processed food waste to minimize its biosafety risks as a feed ingredient for animals [28,178].

In contrast, feeding food waste to food-producing animals in the European Union was banned in 2002 [179] because the outbreak of foot-and-mouth disease (FMD) that occurred in the UK in 2001 was associated with feeding uncooked food waste to pigs. However, it is interesting to note that the FMD outbreaks that occurred in Japan (2010) and South Korea (2010–2011) had no connections to feeding food waste [180,181]. At about the same time, the BSE crisis occurred in the European Union

and resulted in banning the use of all processed animal protein by-products in animal feeds [182]. However, no evidence has ever been observed or reported showing that pigs, poultry, or fish are capable of naturally developing or transmitting prions attributed to TSEs such as BSE [183]. Therefore, from a feed safety perspective, feeding food waste containing animal-derived food products from any species to pigs, poultry, and fish should not be a concern for controlling TSE transmission. As a result of these regulations, only about 3 million tonnes of the estimated total of 102 million tonnes of food waste generated in the European Union is fed to animals [48]. However, if a food waste source can be verified to have no risk of contamination with meat, fish, or other animal by-products, it can be approved for feeding animals. In addition to the influence of FMD and BSE on European Union regulations, concerns about the risk of spreading of avian influenza and Newcastle disease to poultry have also been attributed to feeding food waste in the United Kingdom [184]. Some researchers have questioned whether the European Union goal of eliminating disposal of biodegradable waste in landfills by 2025, as specified in the EU Waste Framework Directive, can be achieved without diverting more food waste into safe animal feed [28]. Dou et al. [48] proposed that by using adequate thermal processing technologies and revising current regulations, the conversion of food waste into animal feed is the only viable option among all disposal alternatives to reduce environmental impact, conserve resources, and improve food security.

In the United States, feeding uncooked or improperly heated processed food waste contaminated with *Salmonella*, *Campylobacter*, *Mycobacterium*, *Trichinella*, *Toxoplasma* [103], and *Clostridium* [185] to swine was viewed as an initial public health concern several decades ago. In fact, *Trichinellosis* was one of the most devastating parasites in pigs and humans in the early 1930s to 1950s and was associated with the feeding of food waste containing meat scraps [186]. However, the United States pork industry is now free of *Trichinella* and the detection of positive cases has been maintained at 0% [187]. Because of the risks of parasite and pathogen transmission from feeding uncooked food waste to pigs, the Swine Health Protection Act was implemented in 1980 that requires food waste containing animal tissues to be thermally processed at 100 °C for 30 min at licensed facilities to destroy these biological hazards before feeding to swine [188]. In addition, feeding food waste containing mammalian tissues to ruminants is prohibited due to the risk of BSE transmission [189]. Current laws and regulations for feeding food waste to swine vary among states [190] and are primarily based on feed safety concerns involving animal-derived food products. Although several states have allowed licensed operations to feed heat-treated food waste to swine in the past, new national efforts are underway to increase processing of food waste into safe animal feed [191].

However, heightened concerns about the potential risk of introduction of African Swine Fever and other foreign animal disease viruses into the United States from food waste containing animal-derived food products obtained from international airlines and cruise ships have become a barrier to achieving this goal [163]. The USDA-APHIS [174] conducted a qualitative assessment of the likelihood of ASFV entering the United States from legal regulated garbage and concluded that there was a low likelihood and moderate uncertainty of ASFV entry from outside the U.S. Biosecurity concerns about feeding food waste to swine have been based on historical references to the risks of transmission of ASFV [192], Classical Swine Fever [193], and swine vesicular disease [194] from feeding food waste collected from international airports that contained infected pork products to swine. Feeding uncooked food waste has also been associated with ASFV transmission in traditional backyard and free-range pig production systems globally [195–197]. The ASFV has been shown to survive in pork meat, fat, and skin for many months [198]. However, by diverting these potentially high-risk food waste sources to non-feed resource recovery and disposal, or by implementing and enforcing strict regulations to ensure adequate thermal processing for complete virus inactivation, these potential biosecurity risks can be avoided.

Adequate Thermal Processing Minimizes Feed Safety Risks of Food Waste

Food waste that has not been adequately heat-processed may potentially contain pathogenic bacteria, prions, and viruses. As a result, countries that allow the recycling and processing of food waste into animal feeds have implemented regulations that require thermal treatment to destroy various

biological hazards. Government regulations in the United States require heating food waste for 30 min at 100 °C [188]. In Japan, Ecofeed manufacturers are required to heat food waste containing meat for at least 30 min at 70 °C or for 3 min at 80 °C [178]. In South Korea, all types of food waste must be heat-treated for 30 min at a temperature of at least 80 °C. If the food waste is used in wet feed production, it is first heated to at least 80 °C and then mixed with corn or rice husks to standardize moisture content to about 70–80% [28]. For dry feed production, food waste is dehydrated using hot air (390 °C) for sterilization, which increases shelf life and minimizes nutritional losses from spoilage [28]. In contrast, current EU regulations allow food waste to be used as animal feed only if it can be guaranteed that there is no risk of contamination with meat, fish, or other animal products [28].

With the exception of prions, the time (30 min) and temperature (100 °C) required for thermally processing food waste in the United States are adequate for inactivating the major parasites and pathogenic bacteria and viruses of greatest concern (Table 8). García et al. [70] confirmed that heating food waste at 65 °C for 20 min has been shown to be adequate for reducing *Salmonella*, *Escherichia coli*, and *Staphylococcus aureus* below levels deemed safe for animal feed. Therefore, use of appropriate thermal treatment protocols can adequately inactivate all of the parasites, bacteria, and viruses that may be present in various sources of food waste to minimize feed and food safety risks, even if these sources contain animal products that are of greatest concern.

8.4. Solutions to Overcome Biosafety Concerns of Using Rendered Animal By-Products and Thermally Treated Food Waste in Animal Feed

Managing risk of microbial contamination in all feed ingredient supply chains continues to increase in importance for preventing the spread of animal diseases domestically and internationally, but it requires further research and process development [199]. Minimizing pathogen contamination in feed ingredients is a dynamic process that has changed over time and can involve various frameworks for decision-making [200]. In the United States, the implementation of the Food Safety Modernization Act has shifted the focus of regulating human and animal food safety from responding to contamination toward preventing it [201]. This requires the use of a Hazard Analysis and Risk-Based Preventative Controls (HARPC) system to identify preventative controls to avoid reasonable or foreseeable food safety hazards introduced or present in the human or animal food supply chain from either a domestic or an international source. The HARPC system is broader in scope than the traditional Hazard Analysis and Critical Control Points (HACCP) system, and not only focuses on process preventative controls, but also includes other preventative controls such as supply chain and sanitation preventative controls. Although HARPC plans for animal feed are focused on preventing physical, chemical, and biological food safety hazards, they do not specifically require consideration of viral contamination in feed. However, most principles and preventative controls including process, supply chain, sanitation, and sanitary transport preventative controls can be effectively applied to prevent and control viral contamination in feed ingredients.

As described in this review, the risk of transmission of TSEs from ruminant-derived carcass tissues in rendered by-product meals and food waste is perhaps the greatest concern. It is now possible to accurately identify raw materials that contain TSEs to substantially minimize this risk. Several research groups around the world have developed analytical methodologies to identify species-specific DNA using polymerase chain reaction (PCR) in samples where the DNA may be partially degraded [202,203]. In addition, enzyme-linked immunosorbent assays (ELISAs) that are capable of differentiating skeletal muscle in protein meals from other tissues have been developed [204]. Furthermore, a Surround Optical Fiber Immunoassay (SOFIA) and specific monoclonal antibodies for brain prion protein from hamsters, sheep, and deer appear to be capable of detecting extremely low concentrations of brain prion protein molecules [205]. Therefore, there are several emerging opportunities to provide surveillance of the presence of prions in rendered animal by-products and animal-derived food waste sources to determine if cross contamination occurred in feed supply chains.

New technologies have also been developed and are available to thermally process high moisture food waste sources into dry, pathogen-free feed ingredients. For example, patented technologies,

including enzymatic digestion at 55–57 °C, pasteurization at 75–77 °C, filtering, and pH stabilization (2.8 to 3.0), are being used to process small and large particles of supermarket food waste to preserve nutritional quality and digestibility while eliminating pathogens [206].

9. Next Steps

A renaissance is needed to reimagine and redesign all stages of our global food supply chains to better cope with the increased losses of food resources caused by global human, animal, and climate health crises. As described in this review, there is enormous potential to significantly contribute to achieving the UN Sustainability Development Goals of responsible consumption and production, reducing climate change impacts, improving life below water, and improving life on land by repurposing food waste streams from pre-harvest to post-consumer stages of supply chains. Although there is ample justification and incentive to do this, government policies and regulations must be reformed using a more holistic approach that will mandate recovery and recycling of greater amounts of valuable nutrients from various food waste streams into animal feed. Governments could provide economic incentives or initial subsidies to encourage entrepreneurs to develop the necessary modern infrastructure to facilitate collection, provide adequate capacity and modern thermal processing equipment to ensure biosafety of dehydrated waste streams and create market channels that connect these supplies with commercial animal feed manufacturers. High-risk food waste sources that may potentially be contaminated with disease-causing biological agents can be identified and diverted toward other useful recycling processes such as biofuels and biogas production or composting to avoid possible disease transmission.

As the global animal feed industry continues to evolve toward sourcing and using feed ingredients with high nutritional value and low environmental impact, additional Life Cycle Analysis determinations are needed for various sources of dehydrated food waste and rendered animal by-products that animal nutritionists can use when formulating eco-nutrition feeding programs for food-producing animals. However, additional animal nutrition studies are urgently needed to develop more robust and comprehensive ME and digestible nutrient composition databases, and to develop accurate prediction equations of various food waste sources for swine and poultry, to encourage animal nutritionists to fully capture the nutritional and economic value of food waste sources when formulating nutritionally adequate and cost-effective complete animal feeds. Furthermore, new risk assessments should be conducted, and extensive biosecurity protocols should be developed based on best biosafety practices, especially for pathogenic viruses, to minimize risk of pathogen and prion transmission through processed food waste sources used as animal feed. Finally, governments, citizens, entrepreneurs, and all sectors of food supply chains need the courage to build food waste collection and processing infrastructure that is economically and environmentally sustainable, using life cycle assessments as well as regulated and certifiable biosafety conditions to create a new model of food sustainability.

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