Review

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Abstract

The swine industry represents a significant contributor to global meat supply but also exerts considerable pressure on natural resources through feed production, greenhouse gas (GHG) emissions, and nutrient losses. The integration of food industry by-products into pig diets offers a promising pathway to mitigate these environmental impacts while maintaining productivity and animal welfare. Such by-products can serve as nutritionally valuable feed ingredients, reducing waste streams and supporting the principles of a circular economy. This review synthesizes current knowledge on the nutritional properties, environmental implications, and economic advantages of incorporating food industry by-products into pig feeding systems. It further outlines the challenges related to feed safety, variability in composition, and regulatory aspects. Overall, the sustainable valorization of food processing residues as animal feed represents a viable strategy to reduce the environmental footprint of pig production without compromising growth performance or health outcomes.

Keywords: circular economy; by-products; environmental footprint; sustainable development goals; pigs

1. Introduction

The growing global demand for food—driven by population growth, longer life expectancy, and rising living standards—poses major challenges for sustainable agriculture. By 2050, food demand is projected to increase by up to 50%, intensifying pressure on agricultural systems to boost productivity while minimizing environmental impacts [1–3]. This pressure is further exacerbated by climate change, urbanization, and land-use transformation, which collectively constrain the availability of natural resources [4,5]. Both crop and livestock production are under growing scrutiny due to their competing demands for land, water, and energy, as well as their contributions to air, water, and soil pollution [6,7]. Global pig production has increased by 140% since the 1960s. The rising world population and the improvement of socioeconomic conditions in many countries have led to higher meat consumption, including pork [8]. Global pork production benefits from cheaper feed and higher productivity, but it faces challenges from geopolitics and ongoing disease risks. Swine production's role is essential for the global economy and food security; however, its significant impacts -including high use of water, increased feed consumption, land use, greenhouse gas (GHG) emissions, food loss- are pushing the environment to its limits [9,10]. Modern pig production faces

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growing economic, environmental, and health-related challenges, including rising feed and energy costs, limited resources, and increased emissions [11].

Feed production represents the largest single cost and environmental input in intensive livestock systems, accounting for 65–85% of total farm-gate value for poultry and pigs [12]. Feed represents the largest share of both economic and environmental costs in pig production, making ingredient selection and formulation critical considerations [13–15]. Beyond its effects on animal health, welfare, and productivity, feed composition also influences farm profitability and overall environmental performance, particularly in relation to GHG emissions, land use, fossil energy consumption, and water quality [15,16]. The competition between feed, food, fuel, and fiber production—the so-called 4F challenge—intensifies the need for sustainable alternatives that minimize resource conflicts. Rising demands for land and water, coupled with the expansion of energy crop cultivation, highlight the necessity of more efficient and environmentally sound feed solutions [17,18]. Sustainable practices such as waste reduction, diet reformulation, and water-efficient cropping have already shown potential to reduce environmental burdens [19].

Within this framework, reducing the environmental footprint per unit of animal product is essential [17,18,20]. Incorporating alternative feed ingredients with lower ecological costs, higher nutrient availability, and better cost-efficiency has become central to modern pork production systems [21]. While pigs typically have smaller carbon footprint per kilogram of meat compared to ruminants, due to their better feed conversion efficiency, their total environmental impact remain high because of the extensive scale of global pig production [22]. Pig production systems differ in their capacity to achieve key sustainability objectives, including reduced environmental and climate impacts, minimized land use, economic viability, and enhanced animal welfare [23]. However, the broader understanding of sustainability can give rise to dilemmas that require trade-offs [24]. This complexity is also evident in the Sustainable Development Goals (SDGs) [25], where progress toward one goal may inadvertently have negative effects on others.

Strategies like improving feed efficiency, using precision farming techniques, and incorporating agricultural by-products into pig feeds are becoming more popular [26,27]. Adopting a circular economy approach in livestock production, which utilizes agricultural by-products and co-products, can enable the reduction, reuse, and redistribution of resources [27].

Potential by-products which may be considered for swine diets may be classified from their primary product origin as follows: a) Grain: distilling by-products/co-products, brewing by-products, milling by-products, baking by-products, b) Animal: milk by-products, meat by-products, egg by-products, c) Vegetable: potato by-products, cull beans, field peas, c) Sugar and starch production: cane, beet and corn molasses, salvage candy. Former Food Products (FFPs), also known as ex-foods, may offer a valuable opportunity to enhance resilience in animal feeding systems. Given their strong nutritional properties, FFPs show considerable promise for consistent inclusion in animal diets. However, their use and potential benefits in animal nutrition are not yet fully explored. Using food industry by-products in pig diets helps address these problems. It diverts waste, reduces environmental stress, improves feed efficiency, and supports a circular economy that keeps resources in use rather than wasting them [28]. Additionally, this practice supports global agricultural and livestock sustainability policies and helps ease pressure on natural ecosystems.

The objective of this review is to comprehensively examine the environmental, nutritional, and economic implications of incorporating food industry by-products into pig diets, while addressing the associated challenges and identifying prospects for future application.

2. Nutritional Value of Food Industry By-Products

Food by-products encompass a wide variety of materials with diverse nutritional properties (Table 1). These include energy-rich residues, protein sources, and fibrous fractions. Understanding their nutrient composition is crucial for formulating balanced diets.

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Table 1. Beneficial effects of some by-products using in pig diets.

By-product	Major nutrients	Potential inclusion Rate	Beneficial effects	References
Whey	• Lactose • Protein • Minerals	10–15% of diet	• Enhances palatability and digestibility • Rich in essential amino acids	[29]
Brewers' spent grains	• Protein • Fiber • Vitamins	15–25%	• Contains beta-glucans • Improves gut microbiota and immunity	[30]
Bakery waste	• Carbohydrate • Energy	10–20%	• High energy value • higher ADG / lower FCR • No significant effect on performance, quality behavior characteristics and welfare	[10,31]
Fruit/vegetable pulp	• Fiber • Antioxidants	5–15%	• Bioactive compounds support antioxidant status	[9]
Oilseed meals	• Protein • Fatty acids	5–20%	• Partial replacement of soybean meal • Contributes essential fatty acids	[32]

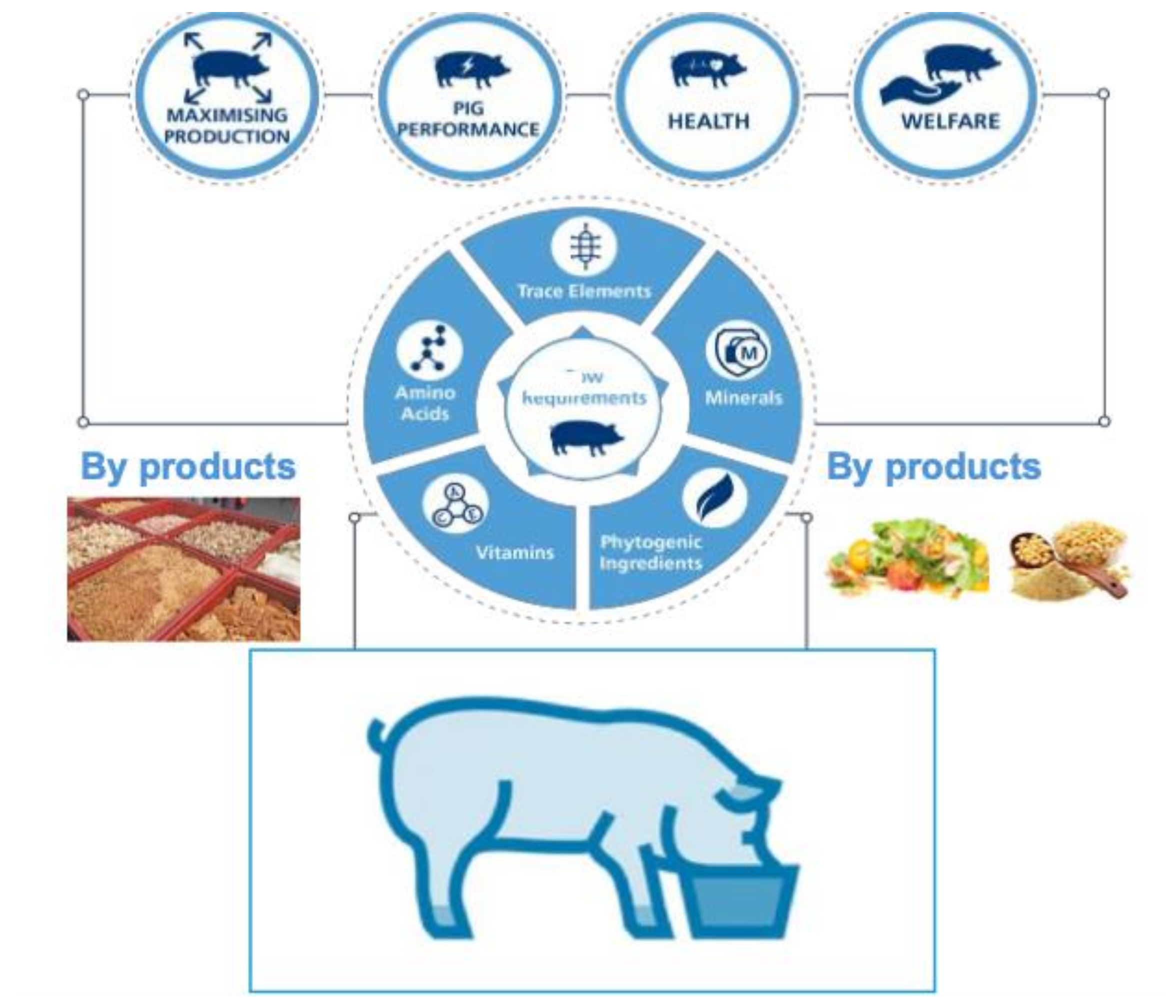

Figure 1. Beneficial effects of some by-products using in pig diets.

FFPs are generally classified into two main groups: those originating from the confectionery sector (e.g., chocolates, biscuits, and sweet snacks) and those from the wearer sector (e.g., bread,

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pasta, savoury snacks, and potato chips), including other high-quality baked goods. These materials are typically high in carbohydrates (starch, simple sugars) and may also contain considerable concentrations of fat [12]. On a dry matter basis, FFPs usually contain around 50–60% starch [33] and about 10% protein, which limits their classification as a significant protein source for livestock [12]. Because FFPs represent a heterogeneous mix of various ex-food types and origins, it is difficult to establish a standardized nutritional composition. Nevertheless, they can serve as an effective source of simple sugars, processed starch, fat, and readily available energy in post-weaning piglet diets. However, their inclusion rates must be managed carefully. Regarding weaners or grower/finisher pigs, further research is required to determine whether higher inclusion levels of FFPs influence growth performance and meat quality [12,31,34–36].

Appropriate processing methods such as drying, pelleting, and ensiling are vital for ensuring feed safety, stabilizing nutrients, and preventing microbial spoilage [29]. The combination of multiple by-products in the same diet can also improve nutrient diversity and balance, compensating for deficiencies inherent in individual materials.

Studies investigating both productive and environmental outcomes of by-product inclusion employ several complementary methodologies (Table 2). These analytical frameworks collectively allow for evaluation of not only growth and efficiency metrics but also sustainability indicators and economic feasibility.

Table 2. Approaches to evaluate environmental and productive impacts of by-products in pig diets.

Approach	Evaluated impacts	References
Life Cycle Assessment (LCA)	Quantification of GHG emissions, energy demand, land and water use, and overall resource efficiency	[10]
Growth performance trials	Average daily gain (ADG), feed conversion ratio (FCR), and carcass characteristics	[30]
Nutritional analysis	Determination of crude protein, amino acid profile, fiber content, and energy digestibility	[29]
Waste diversion metrics	Measurement of the proportion of food residues redirected from landfills to feed use	[9]
Economic assessment	Evaluation of feed cost reduction and profitability associated with by-product utilization	[28]

Several European countries with established swine industries have successfully integrated by-products into feed systems. In France and the Netherlands, for example, incorporating bakery waste led to approximately 15% lower feed-related GHG emissions and partially replaced imported cereals, thus lowering the carbon footprint of production [10]. In Germany, the inclusion of brewers' spent grains improved fiber intake and gut health while substituting soybean meal with a sustainable, locally sourced alternative [30]. In Denmark, fruit and vegetable pulp replaced 20–25% of conventional feed ingredients, maintained growth performance, and reduced feed costs by roughly 8–10%, while also diverting large volumes of organic waste from disposal sites [9].

3. Feedstuffs

The applied strategies that concern the generated agro-industrial by-products serve as critical mechanisms in the mitigation of the emerged environmental issues such as global warming, air and water pollution and the GHG emissions. The generated agro-industrial by-products within European Union (EU) are estimated at 16 million tons, with Germany (3 millions of tons), United Kingdom (UK) (2.6 millions of tons), Italy (1.9 millions of tons), France (1.8 millions of tons), and Spain (1.6 millions of tons) forming the major producers. The livestock sector is responsible for a total emission of 10% of the global GHG [37]. Additionally, it must be noted that nowadays the commercial price of cereal grains and soybean products have revealed a remarkable increment which has a direct impact on the livestock field, resulting in increased production costs [38]. Therefore, it is crucial to discover novel

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alternative sources capable of offering opportunities with lower operational costs. The agro-industrial by-products form an intriguing case, since they can be adopted by the livestock industry. In specific, latter can be characterized as raw materials instead of wastes due to their nutritional composition, since they are consisted of a plethora of valuable components. The already existing technologies provide the ability to recycle and re-use them in various applications, such as feed additives [39].

The Regulation (EC) No 767/2009 of the European Parliament and of the Council, refers that as "feed materials" can be characterized the products which are derived from vegetables and animals and provide the ability to fulfill animal's nutritional requirements [40]. Furthermore, latter legislation also includes products which are generated by industrial processing procedures, organic or inorganic compounds with or without feed additives. These products are going to be used: a) for instant oral animal feeding, b) after processing, c) for the development of a compound feed, d) as premixture agents [41]. It is remarkable that these alternative feeding strategies have gained interest, since their final goal concerns the development of enhanced novel feedstuffs with improved quality by incorporating the aforementioned by-products, exerting thus a positive impact on pigs' health and welfare. Table 3 describes the incorporation of agro-industrial by-products into feedstuffs.

Table 3. Addition of agro-industrial by-products to feedstuffs.

By-Product	Age	Type	Concentration	Effects	Reference
Apple	Finishing pigs	Fermented apple supplement	2% w/w	Improved growth performance and feed quality	[42]
	Finishing pigs	Apple pomace	10 or 20% w/w	Promotion of beneficial bacteria Reduced volatile fatty acids emissions Increased FCR	[43,44]
	Piglets	Apple pomace	3.5% w/w	Beneficial effects on gut microbiota and blood parameters	[45,46]
	Finishing pigs	Fermented apple pomace with *Lactobacillus plantarum*		Enhanced feed efficiency, Lowered ADFI without effect on animal's final BW and back fat thickness	[47]
Grape pomace	Finishing pigs	Fermented Grape pomace with *Lactobacillus plantarum*		Improved beneficial bacteria and reduced VFA emissions in faeces	[43]
Strawberry	Growing pigs	Fermented Strawberry pomace with *Lentinus edodes*		Positive effect on the lean tissues	[48]
Mango	Growing pigs	Mango pulp	15% w/w	Improved the efficiency of starch Protein digestion to a certain extent	[49,50]
Tomato	Pigs	Tomato residues	3% or 5% w/w	Slight affection in pork's meat attributes	[51]
	Finishing pigs	Tomato silage	30% w/w	Promotion of growth performance	[52]
Carrot	Finishing pigs	Carrot wastes	20–25% w/w	Increase of FCR Improved meat quality	[44,53]
Olive	Growing-finishing pig	Olive Cake Processing Waste	5, 10% w/w	Reduced backfat thickness and intramuscular fat Changed their fatty acid content Increased levels of MUFA and PUFA Improved-quality indices	[54]
	Piglets	Fermented Mixture of Olive Mill Stone Waste and *Lathyrus clymenum* pericarp with *Pleurotus ostreatus*	5% w/w	Improved antioxidant blood parameters	[55]

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***Cordyceps. militaris* spent mushroom substrate**	Growing pigs	*Cordyceps. militaris* spent mushroom substrate	2g/kg	Improved growth performance and immunoglobulin secretion Enhanced antioxidant activity Reduced cholesterol, and MDA's levels	[56]
Mulberry	Finishing pigs	Mulberry leaves	3,6,9,12% w/w	Higher loin-eye area and increased crude protein's levels Enhanced inosine monophosphate content and amino acids in muscle tissues	[57]
Strawberry	Finishing pigs	Strawberry pomace	10% w/w	improved fatty acid composition in pork meat	[44]

* *feed conversion ratio (FCR), average daily gain (ADG), average daily feed intake (ADFI), body weight (BW), volatile fatty acids (VFA), malondialdehyde (MDA), monounsaturated fatty acids (MUFA), polyunsaturated fatty acids (PUFA).*

According to Lee et al. [42] the addition of fermented apple in finishing pigs' diet by 2% w/w, revealed beneficial effects in some crucial parameters namely, growth performance, daily feed intake, feed efficiency as well as carcass weight. Moreover, apple pomace was incorporated into finishing pigs' ration by 10 or 20% w/w, promoting thus the presence of beneficial bacteria and the reduction of volatile fatty acids emissions. It must be noted that the addition by 10% w/w led to an enhanced nitrogen retention efficiency [43]. Fermented apple pomace with *Lactobacillus plantarum* was included in finishing pigs' feedstuffs leading to significant results with latter's addition exhibiting a positive impact in some crucial characteristics. In specific, feed efficiency was found to be improved, and the average daily feed intake was reduced without affecting animal's final body weight and back fat thickness [47]. A similar pattern was observed after the addition of Fermented Grape pomace with *Lactobacillus plantarum* in finishing pigs' diet. This addition improved the presence of the beneficial bacteria with a parallel reduction of VFA emissions in faeces [43]. Another study examined the incorporation of strawberry by-products in pigs' conventional feedstuffs. In specific, Islam et al. [48], included fermented strawberry pomace with *Lentinus edodes* in pigs' diet and the results revealed beneficial effect on the lean tissues of growers' pigs. Pluschke et al. [49], reported that the addition of mango pulps in a ratio of 15% w/w improved the efficiency of starch and protein digestion efficiency to a certain extent. Another study examined the fortification of pigs' feed with tomato residues by 3 or 5%w/w revealing a slight effect in pork's meat attributes and more specifically in tenderness [51]. Tomato silage was added by 30%w/w of dry matter basis in fermentable liquid diets for growing-finishing pigs, promoting thus their growth parameters, without presenting negative impact on carcass standards [52]. Furthermore, pigs' diet afforded a replacement with carrot wastes by 20-25% w/w. Latter by-products, are consisted of 11.3 MJ/kg dry matter metabolizable energy justifying their utilization as ideal animal feed [58]. Liotta et al. [54] enhanced pigs' feedstuff by incorporating olive cake processing waste in a ratio of 5 and 10% w/w. The results indicated a reduced backfat thickness, a decreased intramuscular fat level, as well as a modification in their fatty acid content. Additionally, MUFA's and PUFA's presence was found to be improved [54]. In another research, a fermented mixture of olive mill stone waste and *Lathyrus clymenum* pericarp (80-20% w/w) with *Pleurotus ostreatus* was used as feed supplement in pigs' nutrition [55]. In specific, the authors incorporated latter mixture in piglets' conventional feedstuff by 5% w/w and the results revealed improved antioxidant blood parameters [55]. Another study in the existing literature examined the effects of *Cordyceps militaris* spent mushroom substrate as a feed additive in growing pigs' diet. The authors stated that the addition of 2g/kg exhibited a positive impact, since it improved pigs' performance, facilitated immunoglobulin secretion and enhanced the antioxidant activity. Furthermore, latter addition reduced cholesterol, and MDA's presence [56]. Liu et al. [57], studied the fortification of finishing pigs' feed with Mulberry leaves by 3,6,9,12% w/w. The obtained results indicated a higher loin-eye area and an increased crude protein profile. Moreover, this supplement exerted a positive impact on animals' health since this addition enhanced inosine monophosphate content and amino acids in muscle tissues.

4. Environmental Benefits

4.1. Greenhouse Gas Emission Reduction

The livestock sector contributes approximately 15% of global anthropogenic GHG emissions, with pork production responsible for roughly 9% of livestock-related emissions [59]. Within the EU, agricultural GHG emissions predominantly stem from enteric fermentation (45%), soil management (38%), and manure management (15%) [60]. Unlike ruminants, pigs generate relatively low emissions from enteric fermentation [61]. Instead, feed and manure represent the most significant sources of environmental impact in swine production systems [62]. Consequently, optimizing feed formulations and manure management practices is critical for reducing the environmental footprint of the sector [63,64].

Replacing conventional feed ingredients with food by-products decreases GHG emissions associated with crop cultivation, fertilizer use, and transport [10]. Moreover, a 10-25% reduction in CO_2-equivalent emissions per kg of pork when by-products are included, is indicated. The reduction in emissions is especially meaningful when imported soybean meal is replaced by domestic by-products, as this substitution decreases emissions from transport and associated deforestation [28].

Feeding piglets by-products as well as reducing GHG emissions, also diverts land, water, and energy away from production of virgin resources, such as cereals and soybean meal [28,29]. The transformation of food processing waste into high-end feed products enables the food industry to reduce dependency on virgin resources, deforestation associated with soy production, and to improve biodiversity [65]. This approach is also in alignment with the main pillars of circular economy and promotes a closed-loop system which converts the potential waste into a valuable resource according to European Union's Circular Economy Action Plan [65,66].

On the other hand -the positive view- the avoidance of landfill disposal, the cost reduction associated with waste management and potential carbon credit initiatives could also provide financial incentives for farmers that implement circular feed strategies [28,67]. Furthermore, the usage of by-products effects positively to several national and international sustainable development goals (SDGs), such as climate change mitigation, lessen of environmental pollution, and the promotion of more sustainable food production [10].

Further studies on the optimization of nutrient content, retention of bioactive compound content in processing, and feed safety may allow the climate and sustainability benefits of this approach to be further enhanced [68–70]. Considering these aspects of integration, the use of food processing waste as pig feed becomes a highly efficient, practical and environmentally friendly means of tackling the dual issues of livestock production and climate change.

4.2. Land and Water Use

The use of industry by-products for feeding pigs, has been found to reduce the reliance on arable land and freshwater resources, and subsequently towards more sustainable agricultural systems, while previous research showed the saving of 15-30% of land use and 10-20% of water footprint, depending on the by-product type and proportion used [9,15,29]. Demand of products such as cereals and soybeans, which cultivation demands extensive land and irrigation could be reduced by repurpose fruit and vegetable pulp, bakery waste and other agro-industrial residues [10,28,31]. This strategy could beneficially effect, by liberating arable land for other purposes -reforestation, biodiversity conservation etc.- but could also alleviate the strain of water resources, which tend to be increasingly limited, highly impacted from climate change.

Decrease in land use and water consumption, is typically major when by-products are produced and used locally, because transportation emissions and the need for extra resources are reduced [66]. Furthermore, by-product integration is consistent with the circular economy initiative promoted by

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the recycle of energy and nutrients instead of wasting them [65,67]. This approach not only contributes to the preservation of natural resources but also enhances the resilience and sustainability of animal production in the wake of the increasing environmental challenges. As a paradigm, precision feeding techniques combined with high moisture by-products can significantly lessen the environmental footprint of swine production and parallelly improve the nutrient utilization efficiency [30,69]. The ongoing advances in by-products processing techniques, such as drying, ensiling and fermentation, contribute to feed stability, the retention of their nutrients and their all-year round availability [68,70].

4.3. Food Waste Mitigation

The redirection of bakery, dairy, and brewing waste from landfills for use as pig feed is a key strategy to address the issue of food waste in the context of climate change adaptation. Methane (CH_4) produced from the anaerobic decomposition organic waste in landfills poses also a significant concern due to its high potential for global warming, considered as more than 30 times more potent than CO_2 over a century [71]. With conversion of 1 ton of food waste into pig feed, it is estimated that approximately 0.3 tons of CO2-equivalent methane emissions can be prevented, and results in a notable decrease in the overall carbon footprint of food production systems [9,10].

Furthermore, approximately the one-third of all food produced globally is either lost or wasted, with environmental, economic, and social repercussions [29]. The recycle of these substances not only decreases the volume of waste sent to landfills but also save nutrients and promotes sustainable resource utilization [28,29]. When food waste residues are consumed instead of traditional crops like soybeans and grains, which are land-, water- and energy- intensive, the environmental impact is further mitigated [10,15].

By-products from local sourcing also increase the sustainability of this solution through reduced emission from transport and by strengthening local circular economies [66]. Also, the addition of residues high in bioactive compounds could have advantages for animal welfare and health without negative effects on growth performance, which would be a double good for environmental efficiencies and efficiencies of livestock systems [68–70].

Future work will need to investigate the optimization of food by-products through selection choice, cost-benefit use, and inclusion rates to maximize emissions reductions and understand impacts on long-term performance of animals to create equivalent verification or measurement protocols of environmental impacts. There is also a need to consider how to incorporate studies that investigate future processing technologies, such as fermentation or ensiling, that optimize nutrient availability because feed safety and availability 365 days a year are critical and can also be a much larger benefit to global food waste reduction [65,67]. Through the strategic by-product use of food processing, pork production systems could significantly contribute to management of waste and waste disposal sustainably, climate change mitigation, and the promotion of a circular economy.

4.4. Circular Economy Integration

Integrating circular bioeconomy strategies—such as manure management for biogas production, alternative feed ingredients, and wastewater recycling—enhances resource efficiency and reduces environmental footprints [72]. Adding food processing by-products into pig diets is a prime example of industrial symbiosis, in which waste streams from one industry are converted to useful inputs for another, creating a low-resource and low-environmental-input closed-loop system. This approach decreases the reliance on fresh feed sources such as soybean meal or grains and can also assist to conserve water, save arable lands, and energy while lowers GHG emissions [10,28]. Moreover, this method fosters circularity within the agri-food system [9,65].

Furthermore, this strategy opens avenues to create new products, such as revalorizing bioactive compounds for the development of functional feed additives that enhance animal welfare and improve meat quality [66,68,69]. The circular economy approach encompasses a comprehensive system that integrates environmental stewardship, animal welfare practices, and practical business strategies in modern pork production.

4.5. Beneficial Effects on Animal Health, Welfare and Performance

Studies show that the use of by-products has no negative impact on growth performance. For example, feed conversion ratio (FCR) is not affected or slightly improved (2.4–2.8 compared to 2.5–3.0 for normal feed), and average daily gain (ADG) is not significantly changed (700–900 g/day) [29,30]. Also, some by-products, like brewers' grains and whey, have beneficial effects on the gut health. They help different types of beneficial microbes grow and outcompete harmful bacteria, which could lead to a decrease of antibiotics use [9]. Finally, the meat quality is not affected in parameters such as protein, fat, and tasty [15].

In addition, some by-products have important compounds like plant-based polyphenols and antioxidants that can improve animal health [73–77]. By enhancing the immune system of animals, can have beneficial effects on animals' health overall [77]. Food industry by-products (e.g., fruit and vegetable peels, seeds, cereal, dairy, beer and pulp) contain important compounds, such as polyphenols, carotenoids, and glucosinolates. For example, grape, tomato waste, red corn cobs, and grape and olive are enrich with these compounds [70,75,77,78]. These compounds have various beneficial effects on immune system, redox status, growth performance and animal health and welfare [79–83]. Recent studies on pigs reported that plant-based polyphenols revealed to benefit growth performance, support the immune system and protect against oxidative stress damage [79,80].

Modern pig production systems are increasingly required to reconcile productivity goals with enhanced animal welfare and reduced environmental impacts, while systematically incorporating circular bioeconomy principles to strengthen resource efficiency and long-term sustainability [72]. Nutrition is a key factor not only in maintaining pig health but also ensuring high standards of animal welfare. Nutritional interventions that enhance animal welfare can concurrently improve productivity, product quality, and overall profitability. Animal welfare has become an important basis of sustainable production and improvements in environmental impact are likely to come at the expense of animal welfare, or vice versa, regardless of cost [23]. Feeding strategies aligned with circular bioeconomy principles leverage local ingredients and by-products to maximize resource efficiency, whereas conventional methods may overlook pigs' changing nutritional needs, resulting in nutrient waste and higher feed costs [84].

4.6. Alignment with the UN Sustainable Development Goals

The evidence synthesized in Sections 4.1–4.5 shows that integrating food-industry by-products into pig diets advances multiple sustainability outcomes through three main mechanisms: (i) substitution of high-impact primary crops, (ii) avoidance of emissions and resource use associated with alternative waste management, and (iii) valorization of bioactive fractions that support animal robustness without sacrificing performance—collectively underpinning SDGs 12, 13, 6, and 15 (Figure 2).

SDG 12 — Responsible Consumption and Production: By-product feeding operationalizes circular-economy and industrial symbiosis principles, preventing waste and retaining nutrients within the agri-food system (Targets 12.2, 12.3, and 12.5). System-level assessments and comparative scenarios show that redirecting former foodstuffs to feed reduces waste generation and enables cascading biomass use [9,85,86]. Governance and safety frameworks enable responsible production and disclosure (Target 12.4) [87,88].

SDG 13 — Climate Action: Life-cycle evidence indicates that by-product inclusion typically reduces feed-related greenhouse-gas emissions per kilogram of pork by roughly 10–25% through (a) substitution of emissions-intensive ingredients and (b) avoided-waste emissions when former foodstuffs are diverted from landfill or other treatments (Targets 13.2 and 13.3) [9,86]. Replacement of imported soybean meal with domestic by-products further limits transport emissions and mitigates deforestation-linked carbon losses [28].

SDG 6 — Clean Water and Sanitation: Substituting irrigated crops with locally sourced by-products reduces blue-water use and improves water-use efficiency (Target 6.4) [89,90]. Coupling by-product inclusion with precision feeding decreases nutrient oversupply and excretion, lowering eutrophication risks and supporting water-related ecosystems (Targets 6.3 and 6.6) [91].

SDG 15 — Life on Land: Demand reductions for land-intensive feed crops spare cropland and relieve pressure on habitats and biodiversity (Targets 15.1 and 15.5) [86,89]. In EU-relevant pork systems, redirecting former foodstuffs to pig feed reduces cropland use and reliance on soymeal imports linked to deforestation risk (Target 15.2) [28].

Performance, welfare, and business viability (enablers across SDGs): Evidence shows no penalty—and in some cases small gains—in FCR/ADG when diets are formulated isonutritionally with common by-products, while certain bioactive-rich streams support gut health and robustness [9,29,30]. These outcomes facilitate adoption by maintaining productivity, while circular-economy governance and safety guidance ensure compliance and trust [87,88].

Suggested indicators for verification: Operational tracking can include: (i) percentage of ration derived from food industry by-products (Targets 12.2 and 12.5) [28,86]; (ii) greenhouse-gas intensity (kg CO_2-eq per kg pork, farm gate) with separate reporting of substitution and avoided-waste credits (Target 13.2) [9,92]; (iii) blue-water footprint per kg pork (Target 6.4) [89,90]; (iv) nutrient excretion intensity (kg N and kg P per kg pork) (Targets 6.3, 6.6) [91,92]; (v) cropland requirement and displacement of the feed basket based on crop-specific land-use intensities, and share of soy/cereals verified deforestation-free (Target 15.2) [28,86,89]; and (vi) median transport distance/tonne-km for by-product sourcing (supports SDG 13 co-benefits).

In sum, the practices detailed in Sections 4.1–4.5 provide coherent, evidence-based pathways for pig production systems to advance progress toward SDG 12 (circular resource use and waste prevention), SDG 13 (greenhouse-gas mitigation), SDG 6 (water-use efficiency and quality), and SDG 15 (land sparing and biodiversity protection)—without compromising animal performance.

Figure 2. Environmental benefits using food by-products in pig diet.

5. Challenges and Limitations

Despite the numerous environmental and growth performance benefits associated with inclusion of by-products in pig feed, several obstacles hinder their widespread use. The primary

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concern is linked to the inconsistency in nutritional value which can greatly vary, based on its source, season of production and the processing techniques [29,68]. This inconsistency negatively impacts to levels of energy, proteins, fiber and bioactive compounds present in feed, which are all critical for animals' health and growth.

Microbiological safety is also an important aspect to consider. Improper handling and storage of fruit, vegetable, bakery, or dairy residue from the food industry can contain pathogenic microorganisms [10,31,65]. Processing can provide a means to alleviate the risks of pathogenic microorganisms while also maintaining the nutritional and functional properties of the resulting feed material [68,69]. Among the different feed materials, FFPs can be a particularly valuable, nutrient-dense feed. However, studying the "safe" inclusion of these products into pig diets should be carried out inclusively [36]. Processing (e.g., baking, extrusion, frying) applied during food processing of raw materials such as grains or tubers can change starch structure and glycaemic index, causing the carbohydrates to become rapidly fermentable and possibly affect gut physiology or metabolism. Also, due to the varied source materials of FFPs, through a standardized pre-processing procedure, some materials may contain traces of packaging or handling materials that should be removed as well. Developing a traceability and certification scheme for feed handling would improve feed safety and would help in formally determining a standard in environments transporting FFP materials. Ultimately, how FFPs can be safely valorized in relation to their environment affects animal health as well as guarantees food safety for the human population.

Adequate formulation of diets is crucial to achieve amino acid, mineral, vitamin, and energy balance with the incorporation of by-products [93]. Nutrient content fluctuations require advanced formulation tools and on-going laboratory analysis. Computer surveillance and feed formulating software can assist in facilitating real-time adjustments so that animals are fed correctly, and growth performance, immune status, and overall welfare are maintained [30,94]. Regulatory restraints also present obstacles, particularly for by-products from animals, treated waste streams, or those that are not classified as safe to feed [28,65]. Guidelines, certification programs, and standardized processing protocols must be made available to facilitate compliance with the law and increase farmers' confidence.

Resolving such issues requires a multi-step approach, including standardization of by-product quality, severe quality control, cooperative agreements between feed producers, food manufacturers, and government authorities, and investment in processing plants. Research should target synergistic use of a range of by-products, fortification methods with basic nutrients, and long-term effects on animal health and performance, as well as environmental sustainability [70,75,77].

6. Future Perspectives

The use of food processing by-products as animal feeds provides a viable means to achieve sustainable innovation in livestock production. Processes such as fermentation, pelleting, and ensiling, besides improving nutrient digestibility and shelf life, also help in preserving bioactive compounds and reducing microbial contamination [29,68]. Such innovations promote better feed efficiency, animal health, and resilience in production.

Precision feeding systems and digital monitoring gear now make it possible to provide real-time evaluation of nutrient intake, growth rate, and metabolic indicators [30,69,79]. The technologies enable adaptive composition of the diet and continuous optimization of by-product inclusion. Tracking the amount of functional compounds also ensures welfare levels and immune system maintenance [27].

Future research directions include the determination of synergistic by-product blends of maximum nutritional and functional quality, supplementation with limiting nutrients as required, and identification of long-term effects on immunity, performance, and meat quality [70,75,77]. Future research should also determine stability of bioactive compounds during storage, their effect on meat quality, and economic feasibility of inclusion of such material into industrial production systems.

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Combined, these technologies can transform food by-products into the focal point of a sustainable pig livestock production.

Both EU and national policies are increasingly guiding the transition toward more sustainable livestock systems by encouraging innovation, implementing emission reduction strategies, and enhancing resource management [95,96]. Policy instruments would accelerate uptake. Incentives such as carbon credits, tax credits, or subsidies for farms that adopt circular feeding strategies would encourage broader industry participation [28,66]. Furthermore, aligning livestock feed policies to national and international food waste reduction targets, sustainability measures, and climate change mitigation efforts can achieve systemic benefits, including reduced environmental impact, improved animal welfare, and add to economic resilience [9,67].

Innovative methods that use multi-objective optimization tools in feed formulation will continue to enhance sustainability in pig production. It was only recently that introducing an equivalent model into the environmental, nutritional, and economic contexts, demonstrated that the right balance of performance vs ecological footprint can be calculated based on a combination of feeds [21]. The activation of these optimization models, along with supporting public policy and targeted incentives (carbon credits or sustainability directed subsidies) can enable the broader implementation of circular feed ingredients in commercial systems. Furthermore, combining this framework with the European Green Deal [97] as well as the Farm-to-Fork Strategy [98], is likely to enhance or accelerate the transition to a more climate-neutrally developed and more resource-efficient livestock sector. A standardized LCA database and regulation guidelines specific to circular feed ingredients would give the scientific as well as legislative assurance for these developments.

Sustainable pork production increasingly depends on careful feed ingredient sourcing, the application of life cycle assessment (LCA), and consideration of antinutritional factors within multi-objective feed formulation and precision nutrition frameworks. Additionally, advancing and implementing strategies that upcycle nutrients from lower-value by-products and food waste streams into swine feed ingredients are critical to reducing the environmental footprint of pork production. Collectively, these approaches support broader One Health objectives and contribute to the transition toward circular agricultural and food systems [99].

7. Conclusions

Feeding pigs food industry by-products is a smart, research-backed way to reduce pollution, use fewer resources, and maintain the health, welfare and productivity of the animals. This practice aligns with efforts to cut down on waste and help combat climate change. Thoughtfully done, to include appropriate processing, careful monitoring, and appropriate regulations – by-products used as feed could be a feasible, long-term solution for the global swine industry.

Together, by tackling these issues and leveraging the ideas described in this study, by-products from the food industry can form the foundation of a sustainable pig production system influencing improved environmental footprints, animal welfare, and circular, resilient agricultural systems.

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Abbreviations

The following abbreviations are used in this manuscript:

GHG	Greenhouse gas
FFPs	Former Food Products
SDGs	Sustainable development goals
FCR	Feed conversion ratio
ADG	Average daily gain
EU	European Union
UK	United Kingdom
LCA	Life cycle assesment
MUFA	Monounsaturated fatty acid
PUFA	Polyunsaturated fatty acid
ADFI	Average daily feed intake
BW	Body weight
VFA	Volatile fatty acids
MDA	Malondialdehyde

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