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Circular Bioeconomy Practices in the Greek Pig Sector: The Environmental Performance of Bakery Meal as Pig Feed Ingredient

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Abstract: Food systems and, to an extent, the pig sector are major contributors of greenhouse gas (GHG) emissions globally. At the same time, significant amounts of waste are produced from the food sector. The aim of this study is to examine the implementation of circular bio-economy practices in the Greek pig sector to improve its environmental performance. More specifically, in collaboration with a pig farm in Northern Greece and a waste management company, the collection and processing of bakery by-products was organized to produce bakery meal (BM) to integrate it in the diets of fattening and growing pigs. Using Life Cycle Assessment (LCA) methodology, the environmental performance of 20% BM inclusion in pig diets was examined in comparison with the conventional feedstock. BM experimentally replaced corn, wheat, barley, and soya bean from conventional feedstock. The Life Cycle Inventory (LCI) was based on the yearly average values of feed and energy consumption to produce 1 kg of living weight of pig on the pig farm. Life Cycle Impact Assessment (LCIA) was conducted with SimaPro v3.5, using Recipe Midpoint Hierarchical v1.6. The LCIA calculations exhibited that BM inclusion in pig diets can lead to significant land occupation decrease, approximately 30%, which is mostly related to reduced wheat and soya beans. The reduction of cultivated croplands also led to reduced fertilizer and pesticide application, which improved marine eutrophication and freshwater ecotoxicity impact by 20% while it significantly reduced risks of human carcinogenic toxicity by 25%. Moreover, the Greek pig sector exhibited a 5% capacity for overall improvement of its environmental performance, which relies on minimizing logistics when the pig farm conducted collection and processing of by-products. A basic assumption of this study is the assessment of bakery by-product quantities in the wider region of the pig farm. The availability of by-products, based on the reported experience, was limited, and the reliability of the supply was frequently disrupted. As such, the supply chain model of the central hub for the collection and processing of bakery by-products is proposed as more efficient for regulating logistic challenges and availability.

Keywords: pig feed; bakery meal; livestock sustainability; circular bioeconomy; life cycle assessment; food chains

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1. Introduction

The earth's ecosystem is facing significant challenges due to climate change. The global warming rate is increasing as anthropogenic activities and related greenhouse gas

(GHG) emissions are expanding due to the increase in world population and modern lifestyle [1]. In this context, and on the verge of meeting human needs while ensuring optimal environmental performance, the European Union (EU) increased efforts to depict sustainability issues of food production and consumption [2,3]. Recently, there has been a growing emphasis on the environmental effects of food systems and especially of livestock production due to their major environmental impact [4,5]. Food systems are responsible for 34% of total GHG emissions at global scale [6], while the livestock's GHG emissions account for 15% of all anthropogenic emissions [7,8]. Indicatively, the production of 1 kg of beef results in the highest level of global warming potential (GWP), followed by the production of 1 kg of pork, chicken, eggs, and milk, consecutively [5]. At the same time, climate change impacts livestock production in aspects such as natural resource scarcity, reduced feed quality and quantity, the prevalence of livestock diseases, heat stress, and the loss of biodiversity [9], also posing a threat to food security [10]. In this context, circular bioeconomy (CBE) practices provide significant opportunities to overcome such challenges since they can improve resource availability and environmental efficiency, lower GHG emissions, reduce the dependency on non-renewable resources, and contribute to climate action [11]. CBE is described as the interaction between bioeconomy and circular economy with the goal of producing bio-based goods, utilizing organic waste, and lowering GHG emissions [11,12]. CBE has been proposed as a promising solution to GHG emissions reduction within the wider agricultural and livestock sectors, while also providing new business and innovation opportunities in traditional primary production [13].

Pork constitutes approx. 40% of the global meat consumption and is regarded as the predominant type of meat consumed worldwide [14]. In Europe, the consumption of pork reaches approx. 34 kg per capita per year [15]. Thus, pig production is an economically significant livestock sector in the EU [16], accounting for approx. 33% of global production [17]. However, the sector encounters several challenges in terms of sustainability. Its contribution to GHG emissions has doubled in the past decade, and at a global level account for 9% of the total livestock emissions [15,18]. More specifically, pig production has traditionally relied on extensive inputs for feed production, energy, and water. In terms of energy, its consumption is attributed mainly to the agricultural production and processing of feed ingredients, but also to the operation of pig farms (i.e., lighting, heating, ventilation, etc.), and to the transportation of feed, manure, and the end-product. Furthermore, due to water scarcity, water consumption and freshwater resources contamination are of crucial importance regarding the sustainability of the sector [19]. These activities can result in increased emissions of GHG, including methane and ammonia, which stem from inadequate approaches to manure management, storage, and waste management [15]. Nevertheless, a significant proportion of the environmental impacts attributed to pig production and the broader livestock sector, amounting to over 60%, stems from the production of animal feed [15,20].

Animal feed represents the most significant expense in livestock production, as it can encompass up to 85% of the farm gate value for various animal products [21,22]. Beyond being a considerable economic burden, feed also highly influences the environmental footprint of the sector [23,24], especially due to its relation to crop cultivation. Previous research has shown that the production of feed represents the largest environmental impact of monogastric livestock production, accounting for 60% of GHG emissions that emanate from the pig supply chain on a global scale [25]. According to estimates, feed production contributes from 50% to 85% of climate change impact, 64% to 97% of eutrophication potential, 70% to 96% of energy consumption, and almost 100% of land occupation for livestock production [26]. In addition, approximately a third of the world's cereal production is consumed by livestock [21]. To this end, given also the pressure exerted by the animal feed supply chain on human food systems, there has been a growing interest in the use of unconventional feed ingredients or food by-products in the formulation of pig diets [4].

Currently, a global tendency towards the transition to circular bioeconomy approaches has resulted in the increase of recycling and reusing of various products that humans cannot eat [22,27]. As such, recovering of food and plant by-products within the animal feed system presents a promising alternative to confront issues related to proper waste management via the reduction of landfill usage, to food security, as well as to resources and environmental concerns [28]. Thus, creating pathways to convert these available bio-resources into feed would provide a viable solution to the increasing volumes of food waste (associated with the world's growing population) and its disposal [29]. For centuries, it has been a common worldwide practice to feed pigs with food waste and residual by-products from food production [30]. However, the EU banned this practice in 2001 due to its link to the illegal feeding of uncooked food waste that contributed to the foot-and-mouth disease outbreak in the United Kingdom [28]. Nevertheless, former foodstuff products, not containing or being contaminated by animal products other than milk, eggs, honey, rendered fats, and non-ruminant gelatin/collagen, are not considered as food waste by the EU and can be incorporated in the feed of productive animals without posing any regulatory issue [22]. Of particular interest are food leftovers known as bakery former foodstuffs (BFF) comprising bread, pasta, biscuits, chocolate bars, snacks, and cereals, which have been produced for human consumption and fully comply with the requirements of food quality laws. However, due to practical or logistical reasons, or issues arising from manufacturing, packaging faults, or other defects (e.g., shape, color, etc.), these foodstuffs are no longer deemed suitable for human consumption. BFF after grinding and possibly thermal treatment are called bakery meal (BM) and their consumption as feed poses no reported health risk to the animals [22]. BM is already used in pig production, mainly during the first life stages, since it contains significant amounts of sugar, starch, and oil or fat, which contribute to its high level of energy. To this end, BM can be used as an alternative ingredient to replace part of the conventional corn and soybean meals, as well as other starch and protein sources, offering an opportunity to enhance sustainability in pig production while reducing the necessity of using specially designated agricultural land [21,31].

It has been estimated that the EU produces approximately 3–3.5 million tons of BFF [21]. In addition, the share of losses and wastage in the bread supply chain ranges between 1.2–13.7% [32–35]. One of the most significant challenges in the successful valorization pathway of BFF is the proper transportation and handling of the BFF through separate collection pathways, since most animal feed production processes require separation of uncontaminated substrates from other materials of animal origin [28,29]. Although BFF can be collected from various points such as bakeries, supermarkets, sandwich manufacturing companies, and households, segregated collection is usually not feasible, due to the high complexity and associated cost [29,32]. Apart from its recovery as feed in livestock production, alternative approaches to BFF management include, among others: composting, anaerobic digestion for biogas production, incineration, and recovery as nutrients in agriculture [29,30,32,36,37]. However, inadequate resources and infrastructure often result in BFF disposal in landfills despite their significant potential for use as a sustainable feed ingredient [21,38–41]. Valorization of BFF and their integration in pig diets could provide a viable strategy for addressing environmental impacts of pig livestock systems, food security issues, as well as sustainable waste management challenges. To this end, the objective of this study is to perform an LCA analysis to investigate the environmental impact of different scenarios for collecting BFF, producing BM, and incorporating it into pig feed rations, to assess the potentiality of BM as an alternative feedstuff to enhance the efficiency and sustainability of the pig livestock sector. The existing literature [38–40] evaluating the inclusion of BFF in pig diets examined the effect on growth performance, while food waste utilization as animal feed exhibited improvement of pig farming environmental and economic sustainability in Canada [41]. The present study focuses on utilizing BFF to produce BM for the Greek pig sector and evaluates the environmental performance of BM as a feed ingredient under different collection practices providing realistic data concerning the viability of a widespread adoption.

2. Materials and Methods

2.1. Background Information

This study was conducted within the context of CPigFeed (https://www.cpigfeed.eu/, accessed on 31 May 2023), a research project for assessing alternative pig feed ingredients and innovative digital tools for the implementation of circular bioeconomy strategies within the Greek pig sector. More specifically, CPigFeed addresses three axes: (i) Scientific: To experimentally study alternative feeding rations for fattening and growing pigs. A pig farm has been supplied with 12.5 tn of BM. The BM was analyzed concerning its physicochemical characteristics and its microbiological quality, and it was integrated in the feed rations by substituting specific ingredients of the conventional feedstuff. The optimal substitution ratio was found to be 20% *w*/*w*; (ii) Managerial: To assess the possibility of creating a supply chain of BM to the pig sector based on the local and national availability of BFF. The pig farm of interest is located in Chalkidiki, northern Greece. The local and national availability of BFF has been qualitatively and quantitatively assessed by addressing a questionnaire to large bakery companies and by collecting data from existing bakery products producing or marketing companies; (iii) Technological: To develop a platform of digital tools for the registration of available amounts of BFF by the bakery industries and related companies, as well as a tracing application for monitoring the transport of BFF and the produced BM.

The production and supply of the BM to the pig farm have been implemented by a waste management company located in Athens, Greece. Nine rounds (or batches) of BM production and delivery have been organized. The total amount of BM produced and delivered to the pig farm was 12.5 tn, comprising BFF that were collected from various sources, transported to Northern Greece for processing (i.e., BM production), and BM interim storage prior to its delivery to the pig farm. BFF that was used to produce BM were obtained from pasta, chocolate, pastry, bread, and pie making industries/companies. The BFF providers were in a broad range of places, mainly in Attiki, Thessaloniki, and Kilkis.

We assessed the environmental performance of BM integration in pigs' rations by following the LCA methodology as described in the Handbook on Life Cycle Assessment [42], Operational Guide to ISO Standards. The lifecycle impact calculations were conducted using SimaPro software v3.5 [43] with Ecoinvent v3.9 [44] and the Agrifootprint database [45]. The goal was to depict and compare the environmental impacts of a 1 kg living pig weight fed with conventional feed and with feed supplemented with 20% *w*/*w* BM. To address the distinct conditions of the Greek bakery market and the project's specific facts, two scenarios for BFF collection and BM production were developed that considered:

- Two BM supply chain models, (i) a central BFF collection hub and a central BM processing facility, and (ii) individual BFF collection and self-processing (BM production) at the pig farm premises;
- The availability and sustainability of three different geographical zones;
- The technological requirements to set up a BM production facility.

2.2. Baseline Scenario: Conventional Feed

The use case of a large-scale intensive system pig farm in Chalkidiki regional unit of the Central Macedonia region has been selected for the environmental assessment. Within a production cycle that lasts 2.3 months, the pig farm raised 1460 piglets (P), 4390 growing pigs (G), 5400 fattening pigs (F), and 900 sows (S); thus, the ratio of F:G:P:S is 4.4:3.6:1.2:0.7. Furthermore, 776.5 tn of conventional feed was consumed to cover the needs of the animals, and 1250 tn of living meat (before slaughtering) were produced. The corresponding diets of each animal category are presented in Table 1, together with the overall energy demands of the farm and the waste production within a production cycle. The consumption of electricity serves the processing of feed raw materials and the cooling of the establishments while heating (thermal energy) occurs only five months per year. The values exhibited in Table 1 are averaged on a yearly basis.

Table 1. System description of the pig farm case for the baseline scenario.

	Input	Piglet	Growing	Fattening	Sows	Total
Herd	Animal number	1460	4390	5400	900	12,150
Feed	Corn (tn/cycle)		78.2	98.9	9.2	186.3
	Corn flour (tn/cycle)		36.8	34.5	4.6	75.9
	Wheat (tn/cycle)		36.8	46.0	9.2	92.0
	Barley (tn/cycle)		27.6	13.8	3.5	44.9
	Bran (tn/cycle)		23.0	23.0	7.0	53.0
	Balancer (tn/cycle)		27.6	57.5	1.5	86.6
	Vegetable fat (tn/cycle)		50.6	28.8	1.0	80.4
	Soybean oil (tn/cycle)		27.6		1.0	28.6
	Soybean (tn/cycle)		39.1	46.0	7.0	92.1
	Marble dust (tn/cycle)		18.4	13.8	4.6	36.8
Energy	Electricity (kWh/cycle)					102.764
	Heating (MWh/cycle)					90–100
Waste	Manure (tn/cycle)					135
	Liquid (m^3/cycle)					6300
Meat production	Living weight, before slaughter (tn/cycle)					192.0–287.5

2.3. Bakery Meal Production and Experimental Feeding

BM is an alternative feedstuff derived from BFF. The integration of BM in conventional feed has been experimentally examined to substitute several ingredients of the conventional feed considering parameters such as salt, sugar, and fat content, which are critical in pig diets (reported by specialists in pig feeding (conductors of experimental feeding)). The desired by-products were divided into the following categories: (a) chocolates, (b) pastries (cakes, croissants, etc.) (c) cereals, and (d) doughs (pie, pasta, etc.). Based on the sources of BFF, the nutritional characteristics of BM are affected. In Table 2, the average characteristics of certain groups of BFF are presented, together with the nutritional analysis of two batches of BM.

Table 2. Nutritional characteristics of potential BFF and the nutritional characteristics of two production batches of BM.

Product	Energy (cal/100 g)	Fat (%)	Saturated fat (%)	Hydrocarbon (%)	Sugar (%)	Fibers (%)	Protein (%)	Salt (%)
Chocolates	531	31.2	18.6	56.1	40.2	4.6	7.0	0.22
Pastry	464	19.2	9.6	63.9	21.5	4.0	7.3	0.71
Cereals	404	10.1	3.8	66.9	16.5	7.4	8.8	0.75
Doughs	323	13.5	5.1	41.8	2.7	2.2	8.2	1.14
1st BM batch	467	22.5	10.7	51.6	7.8	1.0	14.6	
2nd BM batch	453	27.5	13.0	21.4	0.3	3.6	30.0	

A waste management and treatment company (WMT) organized the collection and storage of BFF and the production and delivery of BM to the pig farm. The collection of BFF was based on restrictions imposed from the project partners [46] for max. 10% *w*/*w* inclusion of chocolates in the BFF, the proximity of BFF sources (i.e., a network of collaborating companies that sell or produce products of the categories displayed in Table 2) to the pig farm, and the fixation of logistics. BFF were unpacked and thermally treated in a processing plant located in Kilkis (northern Greece), while an intermediate handling facility was used for intermediate storing of both BFF and BM batches in Thessaloniki (northern Greece). The WMT company reported that stable production of BM was mainly hindered by:

- Short notice of BFF availability;
- Economic burden for distant BFF sources and low available quantities;
- Mixed shipments with other products (not of interest or inappropriate for BM production);
- Falsified documentation regarding the products of a shipment.

With respect to the production of BM, unpacking was reported as the most time-consuming process due to the large quantities of BFF and the manual labor needed. The thermal treatment process was employed to BFF containing egg or milk products, according to current European rules to produce a hygiene-safe feed product [37]. The thermal treatment process employed 133 °C and 3 bar pressure for at least 20 min. The BM-producing facility was equipped with a rotating incineration kiln (PyroRot 540, S.C. PETAL S.A., Huşi, Romania) and a grounding mill. The capacity of the incineration kiln was 3.5 tn and it was operating for four hours per batch, while the nominal electric power was 10 kW and the nominal thermal power was 1700 kW. After its production, BM was transferred from the thermal processing facility to an intermediate storage facility. During summer, BM was stored refrigerated, whereas the rest of the year it was stored at a cool and dry place (ambient conditions).

The experimental feeding trials were conducted with 80 pigs in total at the growing and the fattening stage. Pigs were equally and randomly assigned in two dietary treatments for each farming stage, i.e., conventional feed diet (identified as CG and CF for the growing and fattening stage, respectively) and diet containing 20% *w*/*w* of BM (identified as BM20G and BM20F for the growing and fattening stage, respectively). The BM inclusion rate in the pig diet was based on the results of preliminary feeding trials. The experimentation lasted until the pigs were 178 days old, and the composition of all diets are summarized in Table 3.

Table 3. Formulations of conventional and 20% BM diets.

Ingredients (% *w*/*w*)	CG	BM20G	CF	BM20F
Corn	15	13	12	13
Corn flour	27	25	32	27
Wheat	15	10	14	8
Bakery Meal	-	20	-	20
Barley	15	11	14	14
Bran	9	9	10	7
Balancer	2	2	2	2
Anti-fungus	0.1	0.1	0.3	0.3
Soybean oil	1.2	1.0	-	-
Soybean	15	8	14	8
Marble dust	0.8	0.8	0.8	0.8

The experimental diets excluded the ingredient of vegetable fat since the inclusion of barley and corn complemented the excluded vegetable fat. The inclusion of 20% *w*/*w* BM in growing pig diets resulted in the subtraction of corn, corn flour, wheat, barley, soybean, and soybean oil by 13.0%, 7.5%, 33.3%, 26.6%, 46.6%, and 16.6%, respectively. In fattening pig diets, corn increased by approx. 8.3% after BM addition, whereas corn flour, wheat, bran, and soybean decreased by 15.6%, 42.8%, 30%, and 42.8%, respectively. During experimental feeding trials, the Feed Conversion Rate (FCR) of the pig groups was calculated in Table 4. The inclusion of 20% w/w BM in the experimental feeding diets exhibited 1.15% improved FCR rate, while no differences in enteric fermentation or solid and liquid waste production were reported.

Table 4. FCR of conventional and BM 20% *w*/*w* diets.

	$FCR_{BM,0\%}$	$FCR_{BM,20\%}$
First period (80–123 days)	3.4075	3.4475
Second period (123–178 days)	5.0250	4.7825
Total (80–178 days)	4.33	4.28

Based on the aforementioned data, the basic values for the 20% *w*/*w* BM inclusion scenario are presented in Table 5. The total meat production has increased by 1.15% as implied by the FCR presented in Table 4.

Table 5. System description of the pig farm case for the 20% *w*/*w* inclusion of BM in growing and fattening pigs.

	Input	Growing	Fattening	Sows	Total
Feed	Corn (tn/cycle)	67.7	100.0	9.2	176.9
	Corn flour (tn/cycle)	34.0	28.4	4.6	67.0
	Wheat (tn/cycle)	24.0	25.8	9.2	59.0
	Barley (tn/cycle)	20.2	13.3	3.5	37.0
	Bakery meal	72.6	71.2	-	143.8
	Bran (tn/cycle)	23.0	15.7	7.0	45.5
	Balancer (tn/cycle)	27.3	47.1	1.5	75.9
	Vegetable fat (tn/cycle)	35.1	22.2	1.0	58.3
	Soybean oil (tn/cycle)	23.0	-	1.0	24
	Soybean (tn/cycle)	20.5	25.8	7.0	53.3
	Marble dust (tn/cycle)	17.9	12.8	4.6	35.3
Energy	Electricity (kWh/cycle)				102.764
	Heating (MWh/cycle)				90–100
Waste	Manure (tn/cycle)				135
	Liquid (m^3/cycle)				6300
Meat production	Living Weight, (tn/cycle)				194.2–290.8

2.3.1. Scenario 1: Central Collection of BFF and BM Production

The first scenario is based on real data from the WMT that organized BFF collection based on the proximity of BFF sources, the restriction imposed on the content of max. 10% *w*/*w* chocolate by-products, and in coordination with the stakeholders of the experimental supply chain. More specifically, nine discrete shipments, as displayed in Table 6, were performed comprising collection of BFF from Attiki, Ioanina, Kavala, Kilkis, Thessaloniki, and Katerini. All shipments corresponded to unique suppliers except for the shipment from Thessaloniki that multiple suppliers were involved.

Table 6. The weight, origin, and distance of by-product and bakery meal shipments performed during the project.

Shipment	BFF Origin	BFF Quantity (kg)	BFF Transport Distance (km)	BM Quantity (kg)	BM Transport Distance (km)
1.1	Attiki	389	654	80	202
1.2	Attiki	2149	654	490	202
2	Attiki	1496	650	300	202
3	Attiki	944	650	190	202
4	Ioanina	2192	407	390	202
5.1	Attiki	1200	634	194	202
5.2	Kilkis	7170	174	3700	202
6	Kavala	2500	37	570	202
7.1	Thessaloniki	2000	179	1890	202
7.2	Kilkis	5500	174		
8.1	Katerini	2000	119	1940	202
8.2	Kilkis	3490	174		
9.1	Kilkis	2110	174	3460	202
9.2	Kilkis	1690	174		
Average		2487.85	346.7	974.4	202

Based on the average BFF and BM quantities displayed in Table 6, the BFF conversion rate to BM was 37.9%. The total amount of BM to cover the needs of one cycle of the pig farm with 20% w/w inclusion in the pig diet is approximately 143.8 tn (Table 5), which corresponds to almost 379.32 tn BFF. Furthermore, BFF and BM were transported on average 346.7 and 202 km, respectively.

2.3.2. Scenario 2: Local BFF Collection and BM Production within the Pig Farm

In the second scenario, the environmental performance of local BFF collection and BM production within the pig farm is examined. The total amount of required BFF is assumed to be 379.3 tn per cycle, which corresponds to approx. 5.5 tn per day. The methodology to assess the available BFF quantities was developed based on the concept of minimizing transportation. The methodological steps for calculating the transportation are:

Mapping of Resources

To map potential sources of BFF, business registration websites were searched for the administrative districts closer to the pig farm and for the eligible BFF. Nea Triglia, the pig farm's location, is very close to the road network connecting Thessaloniki and Chalkidiki. The road network runs through urban and suburban areas that increase their population significantly, during summer. Moreover, several important industrial areas can be found proximate to the pig farm. Potential sources have been listed and divided into three groups/zones based on the connectivity and proximity to the pig farm. The groups of potential sources are on average placed within a 15, 75, and 300 km radius related to the pig farm and contain 90, 300, and 900 businesses, respectively. The first zone contains urban and suburban areas surrounding Nea Triglia in Chalkidiki and the industrial area of Lakoma. The second zone includes sources in the city center of Thessaloniki and the industrial and artisanal areas of Thermi and Vasilika, while the third zone includes industrial and artisanal areas of Sindos, Kilkis, and Katerini as well as the enclosed urban and suburban areas.

Quantitative Assessment

The quantitative assessment was based on semi-structured interviews with 50 stakeholders of the secondary and tertiary sector of baked goods. Specifically, a questionnaire was developed and distributed to the enlisted companies, while several companies reported their available BFF quantities and its disposal methods. Based on the replies of the survey, small, medium, and big companies were correlated to an average of 3, 8, and 50 kg of available by-products per day, respectively.

Modelling of Transportation

To model the available quantities and the required distance to cover the daily BFF needs the enlisted companies were divided into small, medium, and large in relation to their work force. Furthermore, the reported kg of BFF to distance covered by WMT rate in Scenario 1 applied for multiple suppliers in urban areas is 0.065 kg/km. As such, the available quantities and total transportation distance are presented in Table 7. Furthermore, Table 7 exhibits the daily available quantities and the distance covered for collection of BFF depending on the capacity of sources.

The total distance to transport 5497 kg of by-products is 586.8 km. The collection is assumed to be performed by a single truck that loads 3.5, 5.5, and 6.8 kg/source on average from 90, 300, and 520 sources located in zone 1, 2, and 3, respectively while the distance between each source is 0.21, 0.3, and 0.34 km in zones 1, 2, and 3 accordingly. Equations (1)–(3) were used to calculate the input of transportation in Table 8.

$$H = x_i \times y_i,\ i = 1,2,3\ (zones);\ x\text{: load in kg},\ y\text{: distance in km}$$

$$f(h) = \sum_{n=1}^{N=520} \left(\mathrm{x}_3 \times \mathrm{y}_3 \times (\mathrm{n}-1)\right), \tag{1}$$

$$f(h) = \sum_{n=1}^{N=300} \left(x_2 \times y_2 \times (n-1)\right), \tag{2}$$

$$f(h) = \sum_{n=1}^{N=90} (x_1 \times y_1 \times (n-1)) \quad (3)$$

Table 7. Available quantities and distances per area and the total distance to be covered daily.

Zone	Registered Businesses	Capacity (%)			Available Quantities (kg)	Average Distance (km)	Total Distance (km)
		Small	Medium	Large			
1	90	90	10	0	315	15	19.2
2	300	75	22	3	1653	60	90.87
3	900	66	29	5	6120	300	477.1
Collection indexes							
BFF availability (kg/d)		3	8	50			
Collection distance (Km/kg)		0.065	0.025	0.004			

2.4. Goal and Scope

The aim of this study is to compare the environmental impact of 1 kg living weight of pig delivered from the pig farm fed, during the growing and fattening stage, with conventional diet versus a diet containing 20% *w*/*w* of BM within one production cycle (2.3 months). Although there is not an organized supply chain of BM production for pig farming, there are several companies that can provide BFF. The two developed scenarios, presented in Figure 1, attempt to depict the average overview of environmental impacts regarding the supply chain of BM. The study is based on the activities of CPigFeed project, considering the available quantities of the Greek BFF and BM supply chain as depicted during the project. The system boundaries of the two scenarios include BFF collection, BM production, conventional feed ingredients production (cultivation, processing, and transport), and animal farming activities, while the baseline scenario includes the conventional feed ingredients (cultivation, processing, and transport) and animal farming activities. To efficiently compare the baseline scenario to the two scenarios that employ BM into the pig feeding diet, we adopted a feed weight to living pig weight conversion rate of 4.33:1 and 4.28:1 for conventional and BM diets, respectively.

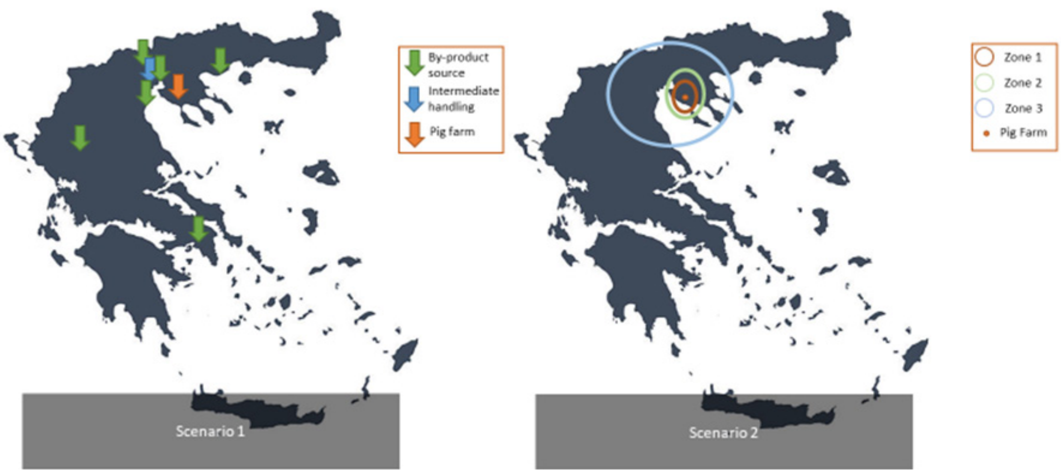

Figure 1. The locations of BFF sources, BM production facility, and the pig farm in Scenario 1 as well as the zones and the pig farm in Scenario 2.

2.5. Assumptions

Life Cycle Inventory (LCI) consist of all the inputs of the system under description for a given Functional Unit (FU). The Life Cycle Impact Assessment (LCIA) was performed with the help of SimaPro software v3.5, and several assumptions were made to specify LCI.

1. The FU of the study is 1 kg living weight. As such, all inputs should be divided by the total amount of living weight before slaughter to provide comparable results. Thus, an average meat production is assumed based on the reported 1000–1500-ton production per year, i.e., 1250 ton.
2. The pig farm heating needs are estimated to be 46 tons of pellets per cycle, while heating is applicable only for five months per year. To spread the burden of heating throughout the year, a monthly average is calculated, i.e., 8.3 ton/month, and 19.17 ton/cycle. The energy content of pellet is 4.7–5.2 MWh/ton. To convert pellet consumption to kWh an average of 4.95 MWh/tn is assumed.
3. The detailed feed diet of pigs after introducing 20% *w*/*w* BM is assumed based on data collected during the experimental feeding trials.
4. The conversion rate of BFF to BM is varies between 17 to 40%. Based on the average conversion occurring throughout the project a 38% conversion rate is assumed.
5. The delivery of BM throughout the project occurred irregularly and based on the availability of BFF. The amount of BM produced during the project is not equivalent to the needs of one cycle. To cover the needs of one cycle, it is assumed that each shipment covered 360 km on average and carried 2.553 tn of BFF while for BM the average transportation distance is 202 km and the average weight of each shipment is 973 kg.
6. In Scenario 2, it is assumed that the daily needs of the pig farm are covered by one shipment per day.
7. The shipment of BFF is weighted as net weight without considering the packaging weight.
8. The allocated weight of the incineration kiln is negligible.

2.6. Life Cycle Inventory (LCI)

The constitution of the inventory was based on literature research, experimental data, and communication with the involved stakeholders. With respect to the system boundaries and the functional unit, the elaborated data of life cycle inventories for the three Scenarios are presented in Table 8.

Table 8. Life cycle inventory for the production of 1 kg living weight of pig in the three scenarios.

	Inputs	Baseline Scenario	WMT Scenario	Pig Farm Scenario
Feed (Kg/FU)	Corn	0.81	0.73	0.73
	Corn flour	0.33	0.28	0.28
	Wheat	0.4	0.24	0.24
	Barley	0.19	0.15	0.15
	Bakery meal		0.59	0.59
	Bran	0.23	0.19	0.19
	Balancer	0.4	0.31	0.31
	Vegetable fat	0.38	0.24	0.24
	Soybean oil	0.23	0.1	0.1
	Soybean	0.4	0.22	0.22
	Marble dust	0.16	0.15	0.15
	Water (dm^3/FU)	8.6	8.6	8.6
Energy (kWh/FU)	Electricity	0.45	0.45	0.45
	Heating	0.41	0.41	0.41
	BM thermal treatment (fuel l)		0.16	0.16

Table 8. *Cont.*

	Inputs	Baseline Scenario	WMT Scenario	Pig Farm Scenario
Transport (kgkm/FU)	Transportation		662	332
Waste	Manure (kg/FU) Liquid (m^3/FU))	0.59 0.03	0.59 0.03	0.59 0.03
Emissions to air (kg/FU)	Ammonia Biogenic Methane Dinitrogen oxide Particulate matter	4.3×10^{-2} 1.0×10^{-3} 3.2×10^{-2} 3.3×10^{-4}	4.3×10^{-2} 1.0×10^{-3} 3.2×10^{-2} 3.3×10^{-4}	4.3×10^{-2} 1.0×10^{-3} 3.2×10^{-2} 3.3×10^{-4}

3. Results

First, the hotspots of pig farming are analyzed, followed by a comparison of the two scenarios of BM inclusion to pig diets, and a more thorough look at the results of BM use on the overall sustainability of the pig sector.

3.1. Environmental Hotspots of Existing Practices: Baseline Scenario

The baseline scenario depicts the existing practices of the pig farm used as a case study and is presented in Figure 2. The impact on freshwater eutrophication is the most significant, exceeding 0.03 points, while freshwater ecotoxicity was the second most impactful stage. Freshwater eutrophication is influenced from the handling of liquid manure by almost 90%. For freshwater ecotoxicity, equally important was the impact of maize, wheat, soybean, and soybean oil production. Similarly, marine eutrophication, which is the third most impactful category, was mostly influenced by the production of raw materials for the pig feed. Liquid manure massively influenced the overall impact since it contributed more than 53.7% of the total impact points.

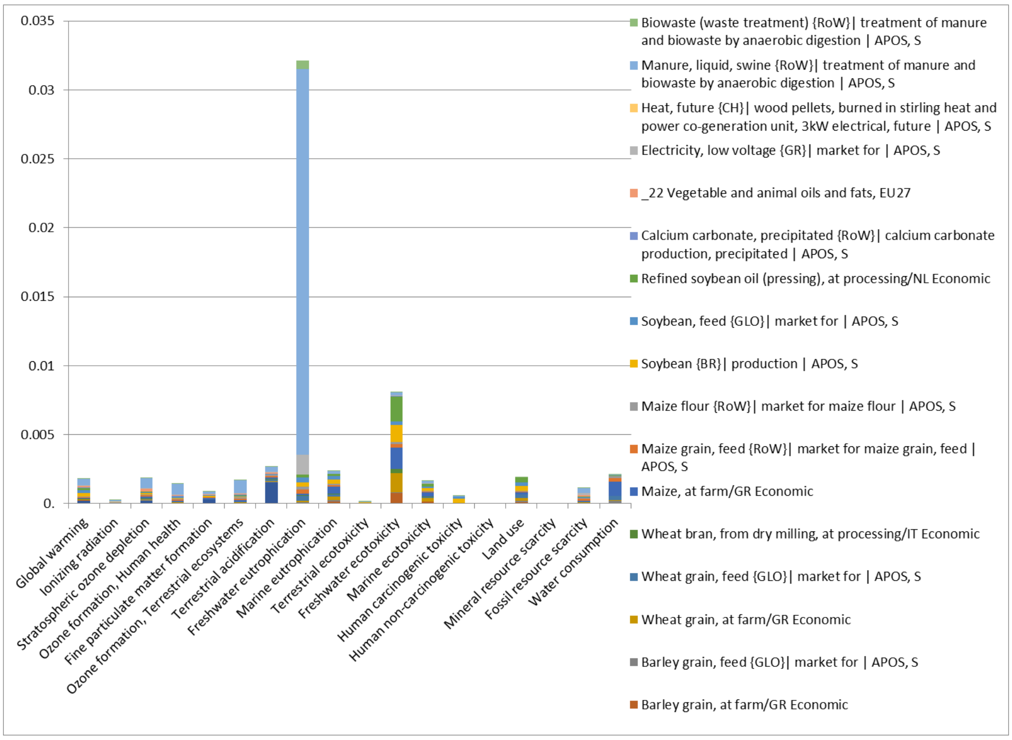

Figure 2. Analyzing 1 kg living weight "Pig Production, Baseline scenario"; method: ReCiPe 2016 Midpoint (H) V1.08/World (2010) H/Normalization; x axis: impact categories, y axis: normalized score to the impact of average global citizen impact for the baseline scenario.

Feed production displayed a higher impact in 13 out of 18 impact categories as exhibited in Figure 3. Most importantly, feed production affected global warming, freshwater and marine eutrophication, freshwater and marine ecotoxicity, as well as land use and water consumption. Maize (cultivation and processing) is attributed with more than 25% of the feed's total impact, while soybean (cultivation and processing) and soybean oil accounted for almost 37% of the feed's production impact.

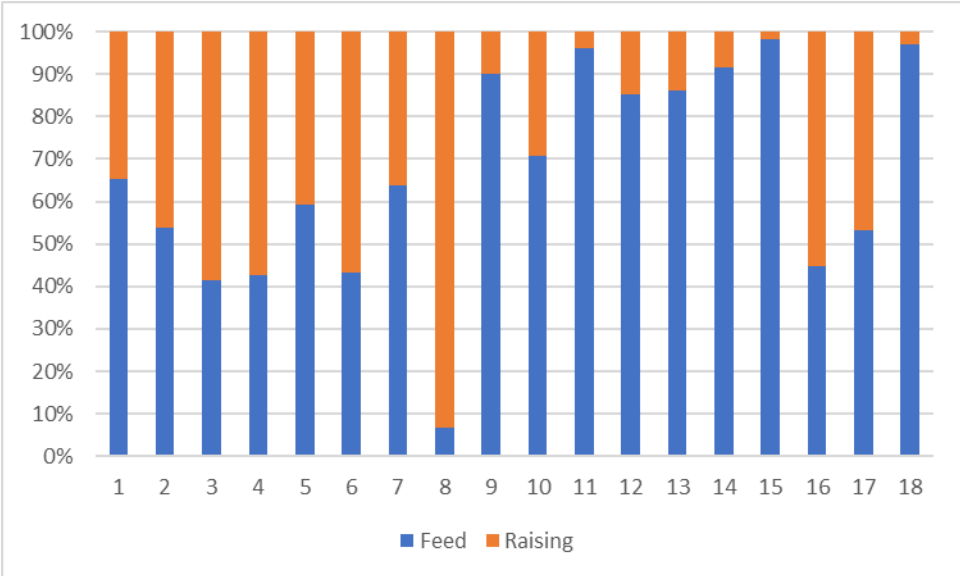

Figure 3. The impact of pig feeding and raising in the baseline scenario; x axis: impact categories, y axis: characterization results of the baseline scenario divided into the stages of feed production and pig raising. The impact of feeding and pig raising in the baseline scenario; x axis: impact categories, y axis: impact results of the baseline scenario divided into the stages of feed production and pig raising.

3.2. Comparison of Baseline Scenario to the BM Scenarios

After inclusion of BM into the pig diet, a slight decrease in the most impactful categories, freshwater eutrophication and ecotoxicity, is observed (Figure 4 and Table A1). The reduction in conventional feed ingredients input has not changed the overview of impact scores since the ranking of impact categories remained unchanged. Quite observable is the decline in freshwater eutrophication and ecotoxicity, land use, and water consumption. The reduction of conventional feed ingredients production will result in less cultivation and decrease in fertilizers, agrochemicals, land, and water use. Totally, baseline scenario accounted for 6.1×10^{-2} points while Scenarios 1 and 2 were attributed with 5.8 and 5.7×10^{-2} points, respectively.

A better overview of the variations between the three scenarios' impact is displayed in Figure 5 and Table A2. Transportation increased in Scenarios 1 and 2 and resulted in higher ozone formation, as well as human non-carcinogenic toxicity and fossil resource scarcity. On the other hand, reduced inputs in pigs' conventional feed ingredients resulted in overall improvement of the environmental performance of pig production. The decrease of impact varied between 3% (for fine particulate matter formation) to almost 30% (for land use) improvement. Quite important, approximately 20%, was the decrease for marine eutrophication, freshwater ecotoxicity, human carcinogenic toxicity, and water consumption. Figures A1–A5 exhibit detailed information of baseline and Scenarios 1 and 2 characterization and normalization results.

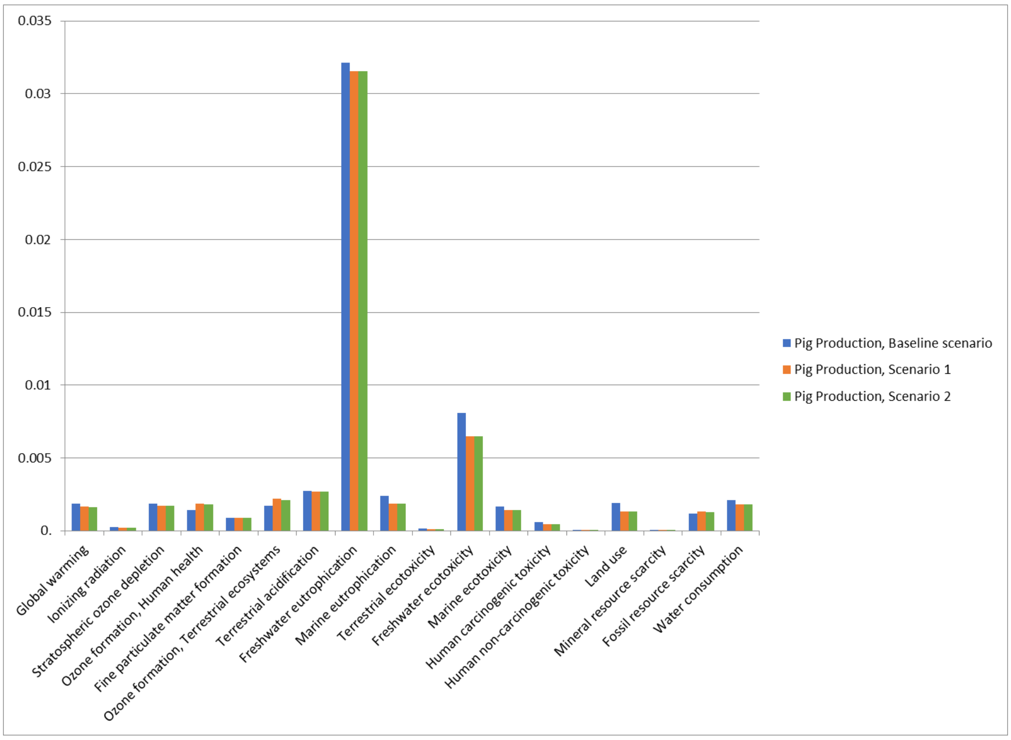

Figure 4. Comparing 1 kg "Pig Production, Baseline Scenario", 1 kg "Pig Production, Scenario 1", and 1 kg "Pig Production, Scenario 2"; method: ReCiPe 2016 Midpoint (H) V1.08/World (2010) H/Normalization; x axis: impact categories, y axis: normalized score comparison for the baseline, WMT, and pig farm scenarios.

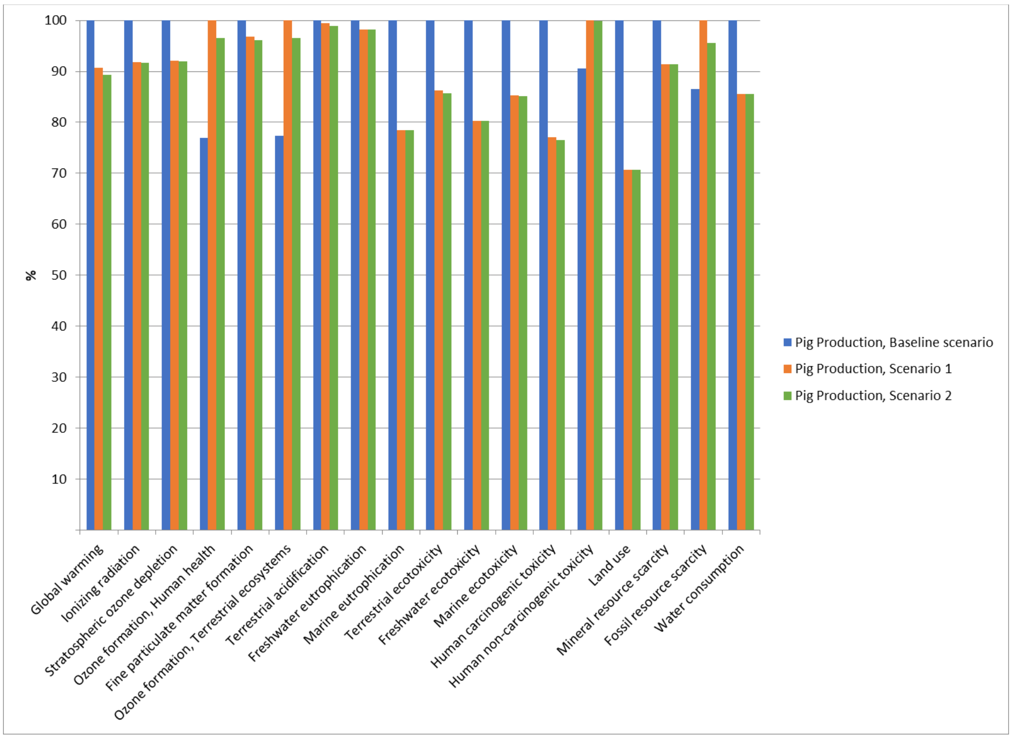

Figure 5. Comparing 1 kg "Pig Production, Baseline scenario", 1 kg "Pig Production, Scenario 1", and 1 kg "Pig Production, Scenario 2"; method: ReCiPe 2016 Midpoint (H) V1.08/World (2010) H/Characterization; x axis: impact categories, y axis: characterized results comparison for the baseline and Scenarios 1 and 2.

3.3. Scenario 2 Environmental Hotspots and Sensitivity Analysis

The inclusion of BM in pig diets is beneficial for the environmental performance of the pig farm, especially for Scenario 2, that transportation of BFF is optimized, and BM is produced on-site. The equipment to produce BM was considered as a negligible environmental burden. As such, the pig farm scenario displayed improved environmental results. Based on the baseline scenario, conventional feed ingredients production accounts for more than 38% of the total impact, while in Scenario 2 it is attributed with 31% of the total impact and BM for 3.3% (Figures 6 and A5). Figure 6 represents the summation of normalized scores depending on the source: Feed production, BM production, Manure management, and Energy consumption divided by the total normalized scores presented in Figure A5.

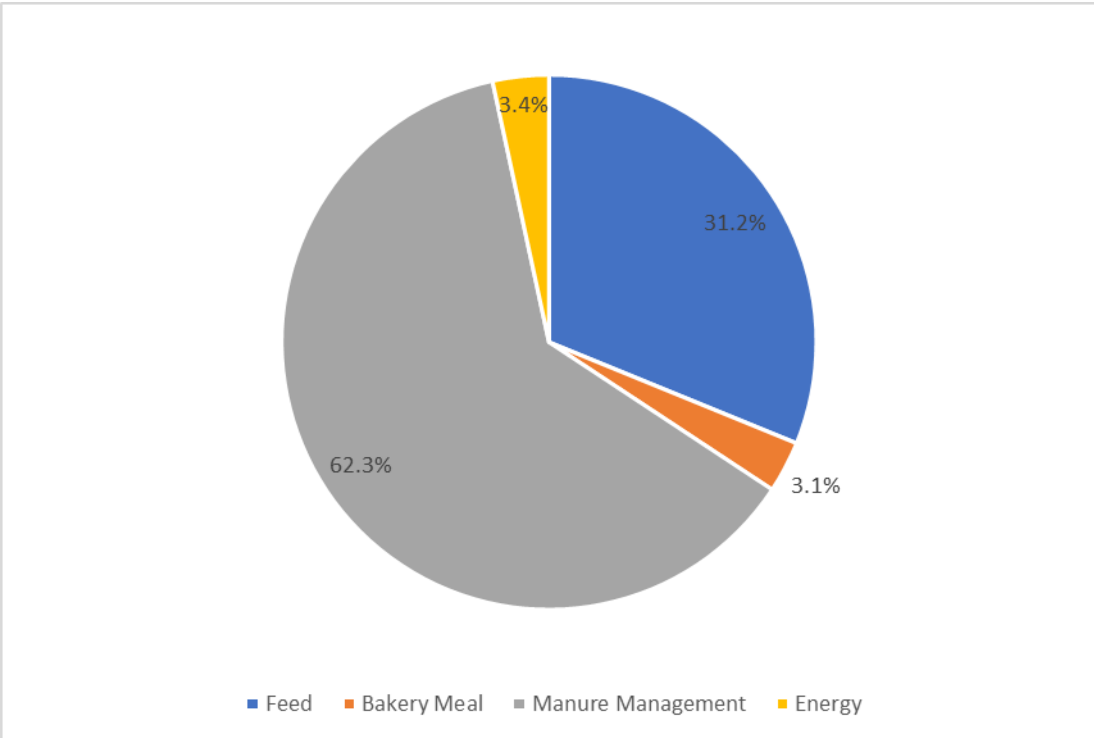

Figure 6. The percentage of impact for conventional feed ingredients production, manure management, BM, and energy requirements in Scenario 2.

The routes reported by the WMT, exhibited in Table 2, can be divided into two categories. The first category includes shipments coming from Attiki, with a BFF to BM conversion rate of 20%, while the second category involves shipments from Central Macedonia, especially Kilkis, Katerini, and Thessaloniki, with a BFF to BM conversion rate of 46%. As such, the first category represented very distant sources with low conversion rate. On the contrary, the second category involved more proximate sources with a higher conversion rate. Moreover, shipments of the first category transferred loads below the average value, while the second category's loads were significantly higher than the average value.

The second category of sources resulted in more efficient BM production. The average conversion factor of 44% would decrease the daily needs in BFF from 5497 kg to 4530 kg. The average shipment load would increase to 3307, thus requiring fewer shipments to cover the daily needs, while the average distance per shipment would decrease from 346 km to 150 km. As such, the corresponding transportation to produce 1 kg of living pig weight would decrease from 662 kg km to 274 kg km, which is lower than in the second scenario. Therefore, it is more efficient to target for BFF with a high conversion rate and for sources with large amounts and close proximity to the pig farm. More importantly, the transportation of BFF to a processing plant results in an extra burden to the environmental performance. As such, it is highly advisable for a pig farm to install the processing equipment and produce BM on site.

The importance of the BFF to BM conversion rate was assessed in a sensitivity analysis, and the results are displayed in Figure 7 (normalization results are presented in Figure A6). The characterized comparative results of the baseline scenario to Scenario 2 with a conversion rate from 20% to 40% show that BM inclusion into pig diets is beneficial even for the lower conversion rate. Apparently, the increased transportation does not seem to influence the environmental outcome. Specifically, ozone depletion, ionizing radiation, marine eutrophication, freshwater and marine ecotoxicity, land use, mineral resource scarcity and water consumption, as well as human non-carcinogenic toxicity remained unchanged. In the rest of the impact categories, the impact scores varied max. 5%. As such, the decrease in conventional feed ingredients production imposes a measurable environmental burden that is not overcome by the low efficiency in BM production.

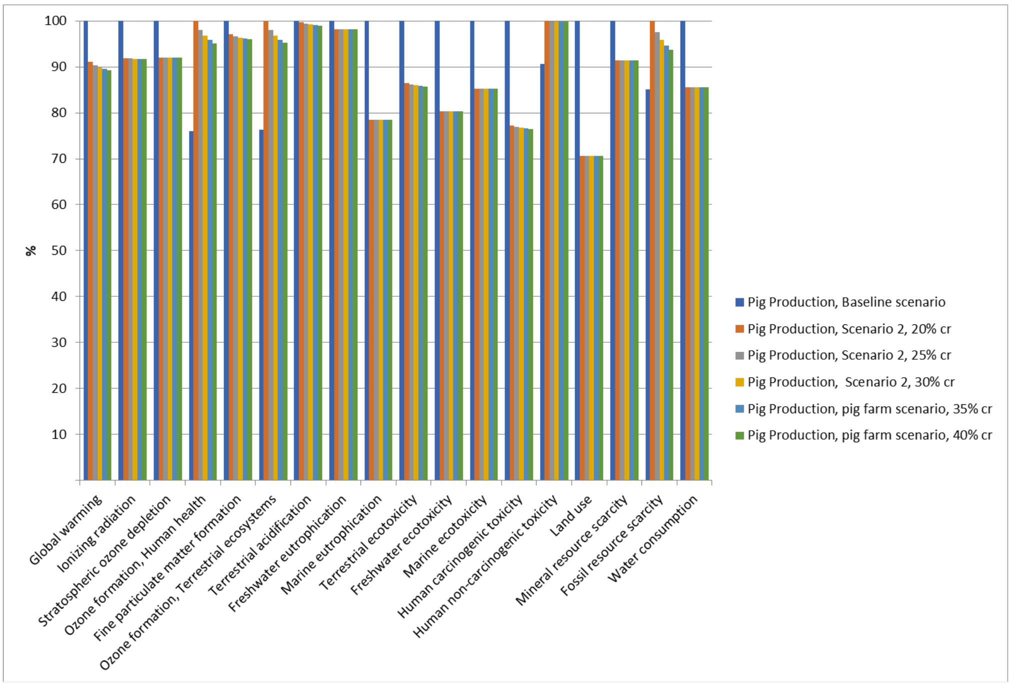

Figure 7. Comparing Scenario 2 with 20%, 25%, 30%, 35%, and 40% BFF to BM conversion factor to baseline scenario; method: ReCiPe 2016 Midpoint (H) V1.08/World (2010) H/Characterization; x axis: impact categories, y axis: characterized results comparison for the baseline, and Scenario 2 for BFF to BM conversion rate between 20% and 40%.

4. Discussion

The environmental hotspots of pig farming using the conventional feedstock mainly attributed to animal feed production, as displayed in Figure 3, influenced mainly global warming potential, marine eutrophication and ecotoxicity, freshwater ecotoxicity, human carcinogenic and non-carcinogenic toxicity, land use, water consumption, terrestrial ecotoxicity and fossil resource scarcity. More specifically, global warming potential was found at the lower limit, approximately 58%, of reported relation to animal feed 50–85%. A total of 90% of eutrophication potential was attributed to animal feed settling to a high level based on the literature, 64–97%, while land use was by 98% attributed to animal feed in accordance to reported numbers, almost 100% [26].

The study examined the environmental performance of upcycling BFF as animal feed. In comparison to conventional feed, BM inclusion, helped decrease the Greek pig sector's environmental impact in fourteen (14) out of eighteen (18) impact categories while in four impact categories, the impact increased. The highest decrease by percentage, based on Figure 5, was achieved in land use approximately 30%, human carcinogenic toxicity almost 25%, as well as freshwater ecotoxicity and marine eutrophication, 20%. Water consumption was also directly affected by the reduced agricultural activity by 15%. Almost 75% of freshwater ecotoxicity originated from pesticides used in crops (see Table A3). Pesticides pose a major pollution risk to aquifers due to their connectivity with croplands [47]. Similarly, more than 80% of land use is directly related to the croplands used for animal feed while a significant percentage is related to forest losses (see Table A4) due to increased cropland needs as also spotted in the Amazonian Forest [48], which is connected to an increase in GHG emissions by 9.2% [49]. Marine eutrophication was solely influenced by nitrate (see Table A5), commonly found in fertilizers applied in crops, which pollutes marine and freshwater basins via leaching [50]. Human carcinogenic toxicity is attributed to airborne emissions of fertilizers, pesticides, and disinfectants used in agriculture (see Table A6) from compounds such as formaldehyde [51]. The corresponding improvement between the baseline scenario and the pig farm scenario per crop for water consumption, land use, marine eutrophication, freshwater ecotoxicity, and human carcinogenic toxicity are displayed in Table 9.

Table 9. The variation of feed ingredients between the conventional feed (CF) and BM inclusion feedstock along with the decrease in water consumption and land use.

Ingredient	Variation between CF and BM (kg/FU)	Water Consumption Decrease (m^3/FU)	Land Use Decrease (m^2 Crop eq)	Marine Eutrophication (kg N eq)	Freshwater Ecotoxicity (kg 1,4-DCB)	Human Carcinogenic Toxicity (kg 1,4-DCB)
Corn	0.08	2.0×10^{-2}	6.0×10^{-2}	1.2×10^{-4}	0	4.0×10^{-6}
Corn Flour	0.05	0	2.0×10^{-2}	3.4×10^{-5}	3.7×10^{-4}	1.3×10^{-5}
Barley	0.04	1.0×10^{-2}	2.0×10^{-1}	$2.3\ 10^{-4}$	0	1.0×10^{-6}
Wheat	0.16	5.0×10^{-2}	1.18	8.0×10^{-3}	1.1×10^{-2}	4.5×10^{-5}
Bran	0.04	0	0	0	0	0
Soybean oil	0.13	0	3.2×10^{-1}	1.0×10^{-4}	1.0×10^{-2}	1.55×10^{-5}
Soybean	0.18	9.0×10^{-4}	1.7	1.16×10^{-3}	2.0×10^{-2}	1.82×10^{-3}

On the other hand, ozone formation as well as human non-carcinogenic toxicity and fossil resource scarcity are the impact categories that were influenced negatively when using BM in pig diets. Ozone formation is mainly attributed to NOx emissions usually emitted by fossil fuel combustion [52]. Ozone formation impact consisted of nitrogen oxides emissions by 92% (see Tables A7 and A8). Despite the decrease in diesel burned in machinery for agricultural activities, the transportation of BFF and fossil fuels used for their processing outweighed these nitrogen oxide (NOx) emissions in the atmosphere. Acephate, an organophosphorus compound, is the main contributor in the human non-carcinogenic toxicity impact category (see Table A9) and is related to agricultural activities with pesticide use [53]. However, fossil fuel combustion for processing of BFF imposed a great influence on human non-carcinogenic factors, which is mainly attributed to crude oil production and refining (see Figure A7). Fossil resource scarcity increase is directly related to the use of fossil fuels for BFF processing.

BM was produced from BFF that are not destined for human consumption. To establish a local supply chain for BFF transported for BM production onsite to the pig farm, two main problems were encountered. Firstly, the need for a proper and safe handling of BFF hindered the process due to lack of equipment. Secondly, the collection of BFF was hindered by two established value/supply chains competing with CPigFeed. During the interview stage, possible suppliers informed that the BFF were either sent to a biogas treatment plant or directly to animal feed without any thermal treatment, which is questionable given the current legislative framework. The use of food waste as animal feed, while respecting EU regulation, appears to be more effective environmentally than anaerobic digestion or composting [41,54]. As such, to succeed in the establishment of a value chain of BM production, several policy-making actions and informative campaigns need to take place.

As reported by the WMT company, BFF collection was also problematic due to the inconsistent availability by the suppliers. Organizing logistics was proven significant for the optimal environmental performance of BM production [41] since transportation of waste is the main environmental burden [55]. Scenario 2 required half the transportation needs compared to Scenario 1 due to the assumed daily availability of BFF and the assumed one shipment per day. Furthermore, to secure an efficient supply chain of BFF, the BFF to BM conversion rate is quite significant since conversion rate influences the required quantities of BFF. Therefore, each BFF source should be assessed qualitatively and be assigned with a conversion factor to avoid shortcomings in BM production. The proximity of BFF sources to the pig farm is also an important parameter that affects the outcome. Scenario 2 projected three zones of possible BFF sources and assumed one pig farm that claimed the assessed quantities. If other local pig farms seek an alternative animal feed, the competition for the assessed BFF quantities will increase. As such, local central hubs of BFF collection will help with the distribution and will bear with the efficiency of the logistics.

The overall impact of BM production and inclusion as a pig feed ingredient was environmentally beneficial. BM production required almost fifteen thousand kilometers of transportation throughout the whole cycle in Scenario 2. The required BM production is 143.8 tons in replacement of approximately 144 tons of conventional feed ingredients, which resulted in an improvement of feed conversion rate (FCR) and of the total pig meat production by 1.15%, which is also in accordance with the literature [35]. Feed efficiency is considered as a key factor to achieve economic and environmental sustainability in pig farming [56].

The conversion of BFF to BM was assumed to be 38% based on the average BM production during the project. However, the WMT company reported that a 20 to 25% conversion rate is quite usual for BM. The sensitivity analysis for five different BFF to BM conversion rates displayed that the results were robust. More specifically, in most impact categories, impact scores remained unchanged while the most influenced impact categories were ozone formation and fossil resource scarcity.

5. Conclusions

The reported routes of by-products clearly highlighted the need to acquire by-products from proximate to the pig farm suppliers and target for by-products with a high conversion factor. Fossil fuel combustion for BFF processing should be replaced to meet the global needs of decarbonization of anthropogenic activities and preservation of fossil resources.

The basic outcome of this study is the improved environmental performance of the inclusion of BM to the pig feed diet compared to the baseline scenario. BM seems to be an alternative pig feed ingredient that is likely to decrease the environmental impact of the pig sector. Furthermore, targeting the reduction of maize, barley, and wheat can lead to significant water consumption decrease, while wheat and soya bean replacement could help with land use impact mitigation. A 5% decrease of the environmental impact of the pig sector is quite promising. BM addition can help increase the sustainability of pig farms and provide stability in times of insecurity in the conventional animal feed ingredients supply chains. Furthermore, it could help sustain a better long-term management of pig farms since BM could bend the seasonality problem of animal feed.

Seemingly, the proposed BM inclusion in conventional pig feedstock address several issues of the pig sector that are related to pig feed production. More importantly, BM can safely replace corn, wheat, barley, and soya bean and help decrease global cereal consumption as animal feed. Furthermore, BM inclusion in pig diets can help decrease land occupied for animal feed production. As such, fertilizer and pesticide application related to animal feed production will decrease and help with water and land restoration and will benefit human health by reducing carcinogenic compound emissions.

To obtain a better overview of BM effects when integrated into pig diets, further investigation is needed. More specifically, the response of the bakery industry should be examined under pilot scale operations. Furthermore, experimental feeding should be also extended in pilot scale. The FCR should be further explored to gain more robust results. Moreover, to provide a more holistic approach for the increase of the pig sector's sustainability, BM use should be examined for its economic influence. Although the increase in sustainability of the food sector globally should be more thoroughly examined by implementing scenarios to depict the reaction of farmers that produce pig feed, food versus feed competition could be significantly improved as well as food security.

Author Contributions: Conceptualization, L.M., G.F.B., S.I.P. and M.B.; methodology, L.M., M.B. and G.F.B.; software, L.M.; validation, L.M., G.F.B., S.I.P., E.A. and S.S.; formal analysis, L.M., G.F.B., S.I.P., M.B. and S.S.; investigation, L.M., A.M., D.G., S.S. and C.K.; resources, L.M., S.S., E.A., A.M. and D.G.; data curation, L.M., M.B., S.I.P., E.N.S., M.-Z.K., A.D., E.A., D.G., C.K. and A.M.; writing—original draft preparation, L.M., M.B., S.I.P. and G.F.B.; writing—review and editing, A.D., A.M., M.-Z.K., E.N.S., S.I.P., C.K., S.S., M.B., D.G. and E.A.; visualization, L.M., M.B., S.S., A.D. and E.N.S.; supervision, G.F.B., E.N.S. and S.I.P.; project administration, L.M., A.M., D.G., C.K. and S.S.; funding acquisition, G.F.B., S.I.P. and E.N.S. All authors have read and agreed to the published version of the manuscript.

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

Appendix A. Life Cycle Impact Calculations

Table A1. Comparing 1 kg "Pig Production, Baseline scenario", 1 kg "Pig Production, Scenario 1", and 1 kg "Pig Production, Scenario 2"; Method: ReCiPe 2016 Midpoint (H) V1.08/World (2010) H/Normalization.

Impact Category	Unit	Pig Production, Baseline Scenario	Pig Production, KAFSIS Scenario	Pig Production, Pig Farm Scenario
Global warming		1.84×10^{-3}	1.67×10^{-3}	1.64×10^{-3}
Stratospheric ozone depletion		1.88×10^{-3}	1.73×10^{-3}	1.73×10^{-3}
Ionizing radiation		2.45×10^{-4}	2.25×10^{-4}	2.24×10^{-4}
Ozone formation, Human health		1.45×10^{-3}	1.88×10^{-3}	1.82×10^{-3}
Fine particulate matter formation		9.06×10^{-4}	8.77×10^{-4}	8.71×10^{-4}
Ozone formation, Terrestrial ecosystems		1.71×10^{-3}	2.21×10^{-3}	2.13×10^{-3}
Terrestrial acidification		2.72×10^{-3}	2.7×10^{-3}	2.69×10^{-3}
Freshwater eutrophication		0.03	0.03	0.03
Marine eutrophication		2.39×10^{-3}	1.88×10^{-3}	1.88×10^{-3}
Terrestrial ecotoxicity		1.49×10^{-4}	1.29×10^{-4}	1.28×10^{-4}
Freshwater ecotoxicity		0.01	0.01	0.01
Marine ecotoxicity		1.66×10^{-3}	1.42×10^{-3}	1.42×10^{-3}

Table A1. *Cont.*

Impact Category	Unit	Pig Production, Baseline Scenario	Pig Production, KAFSIS Scenario	Pig Production, Pig Farm Scenario
Human carcinogenic toxicity		5.79×10^{-4}	4.46×10^{-4}	4.43×10^{-4}
Human non-carcinogenic toxicity		1.04×10^{-5}	1.14×10^{-5}	1.14×10^{-5}
Land use		1.91×10^{-3}	1.35×10^{-3}	1.35×10^{-3}
Mineral resource scarcity		2.19×10^{-7}	2×10^{-7}	2×10^{-7}
Fossil resource scarcity		1.17×10^{-3}	1.35×10^{-3}	1.29×10^{-3}
Water consumption		2.13×10^{-3}	1.82×10^{-3}	1.82×10^{-3}

Table A2. Comparing 1 kg "Pig Production, Baseline scenario", 1 kg "Pig Production, Scenario 1", and 1 kg "Pig Production, Scenario 2"; Method: ReCiPe 2016 Midpoint (H) V1.08/World (2010) H/Characterization.

Impact Category	Unit	Pig Production, Baseline Scenario	Pig Production, KAFSIS Scenario	Pig Production, Pig Farm Scenario
Global warming	kg CO_2 eq	14.72	13.35	13.16
Stratospheric ozone depletion	kg CFC11 eq	1.12×10^{-4}	1.03×10^{-4}	1.03×10^{-4}
Ionizing radiation	kBq Co-60 eq	0.12	0.11	0.11
Ozone formation, Human health	kg NOx eq	0.03	0.04	0.04
Fine particulate matter formation	kg PM2.5 eq	0.02	0.02	0.02
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.03	0.04	0.04
Terrestrial acidification	kg SO_2 eq	0.11	0.11	0.11
Freshwater eutrophication	kg P eq	0.02	0.02	0.02
Marine eutrophication	kg N eq	0.01	0.01	0.01
Terrestrial ecotoxicity	kg 1,4-DCB	2.27	1.96	1.94
Freshwater ecotoxicity	kg 1,4-DCB	0.2	0.16	0.16
Marine ecotoxicity	kg 1,4-DCB	0.07	0.06	0.06
Human carcinogenic toxicity	kg 1,4-DCB	0.01	4.6×10^{-3}	4.56×10^{-3}
Human non-carcinogenic toxicity	kg 1,4-DCB	0.32	0.36	0.36
Land use	m^2a crop eq	11.79	8.33	8.33
Mineral resource scarcity	kg Cu eq	0.03	0.02	0.02
Fossil resource scarcity	kg oil eq	1.14	1.32	1.26
Water consumption	m^3	0.57	0.49	0.49

Table A3. Freshwater ecotoxicity inventory outputs with 3% cut-off.

No	Substance	Compartment	Unit	Total
	Total of all compartments		kg 1,4-DCB	0.2
	Remaining substances		kg 1,4-DCB	0.05
1	Chlorpyrifos	Soil	kg 1,4-DCB	0.06
2	Metolachlor, (S)	Soil	kg 1,4-DCB	0.05
3	Diflubenzuron	Soil	kg 1,4-DCB	0.04
4	Vanadium	Water	kg 1,4-DCB	0.01

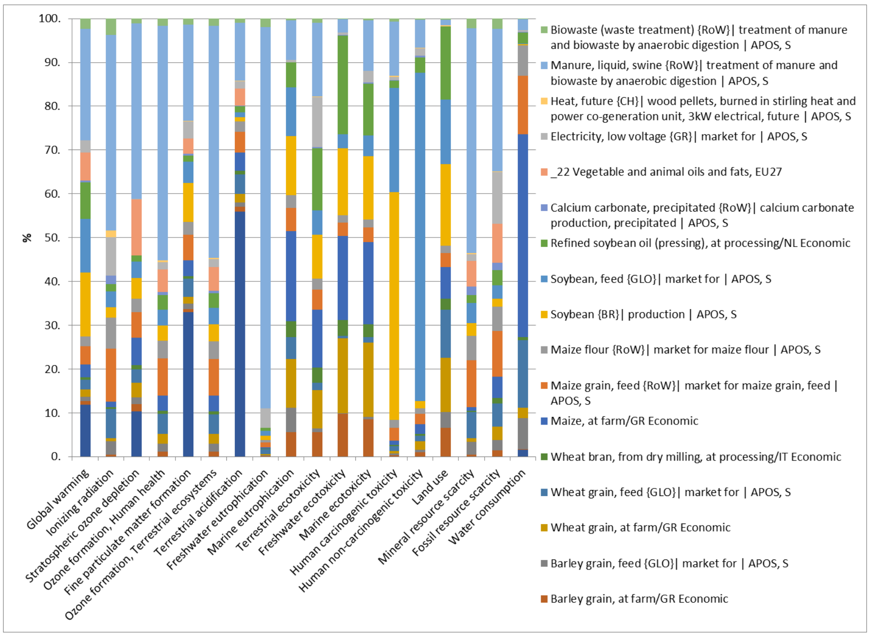

Figure A1. Analyzing 1 kg "Pig Production, Baseline scenario"; Method: ReCiPe 2016 Midpoint (H) V1.08/World (2010) H/Characterization.

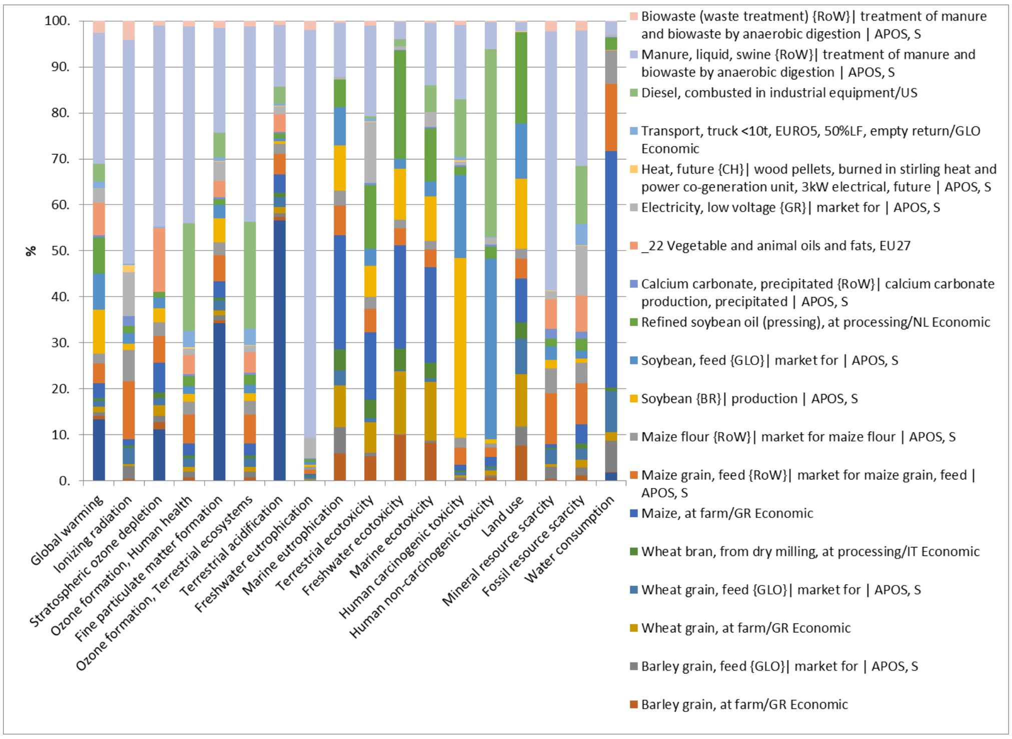

Figure A2. Analyzing 1 kg "Pig Production, Scenario 2"; Method: ReCiPe 2016 Midpoint (H) V1.08/World (2010) H/Characterization.

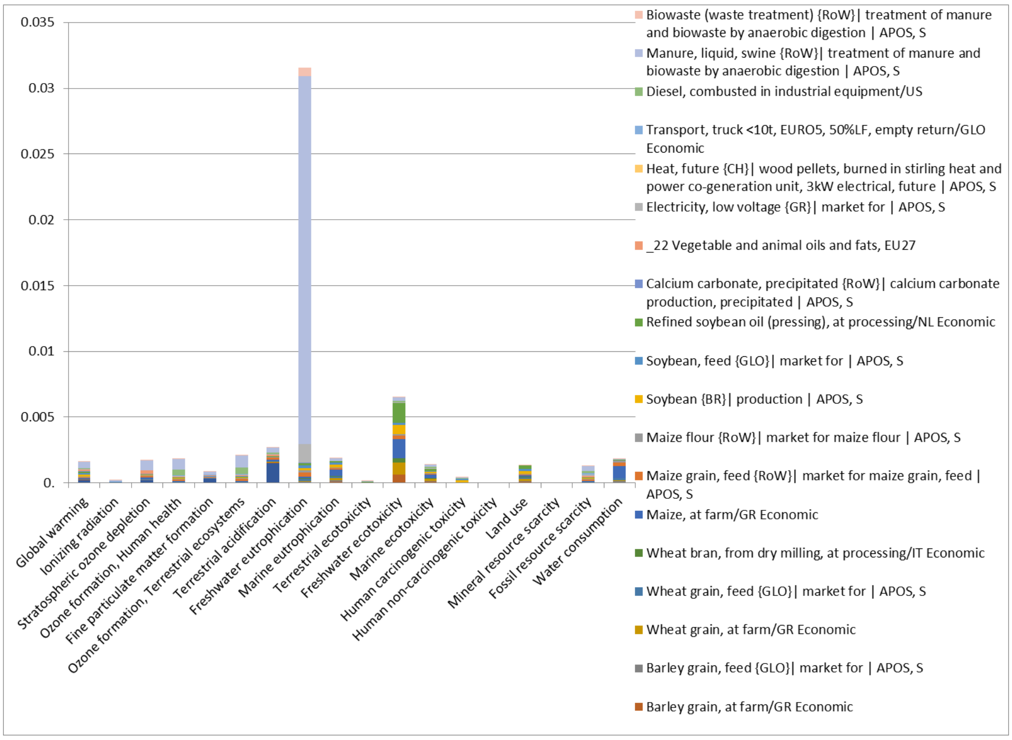

Figure A3. Analyzing 1 kg "Pig Production, Scenario 2"; Method: ReCiPe 2016 Midpoint (H) V1.08/World (2010) H/Normalization.

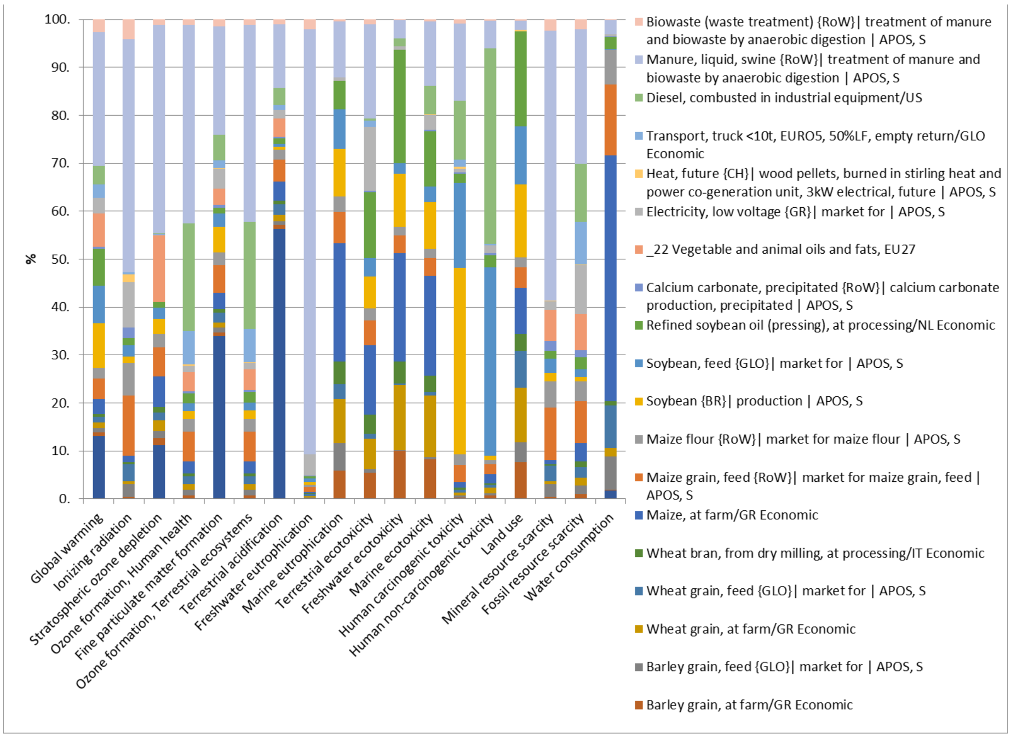

Figure A4. Analyzing 1 kg "Pig Production, Scenario 1"; Method: ReCiPe 2016 Midpoint (H) V1.08/World (2010) H/Characterization.

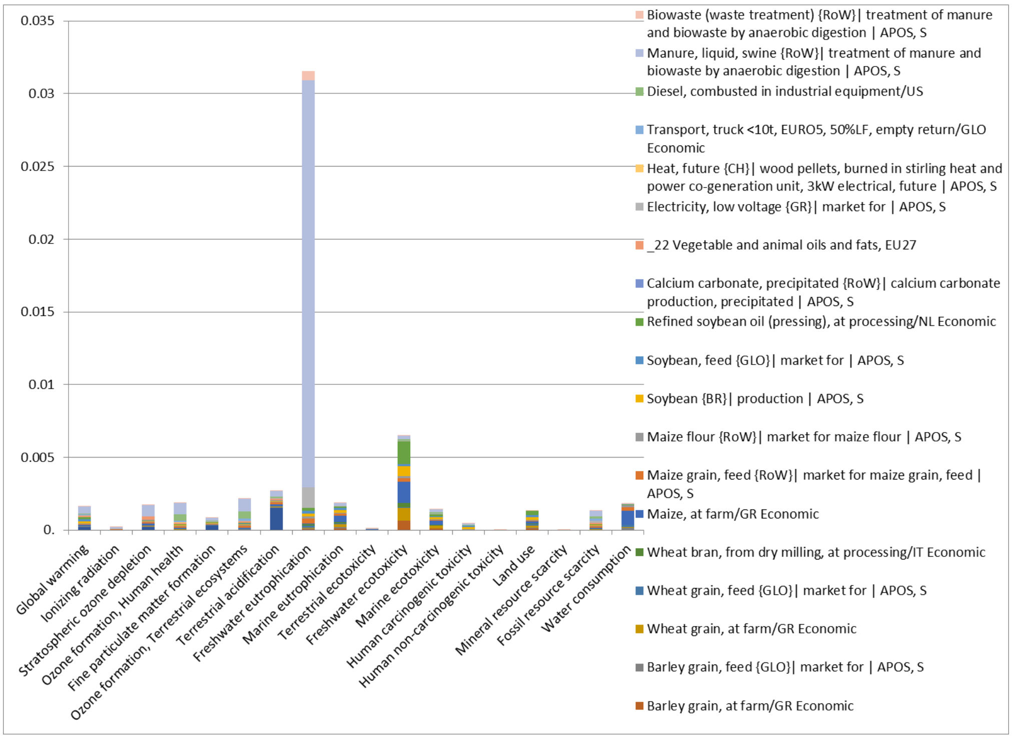

Figure A5. Analyzing 1 kg "Pig Production, Scenario 1"; Method: ReCiPe 2016 Midpoint (H) V1.08/World (2010) H/Normalization.

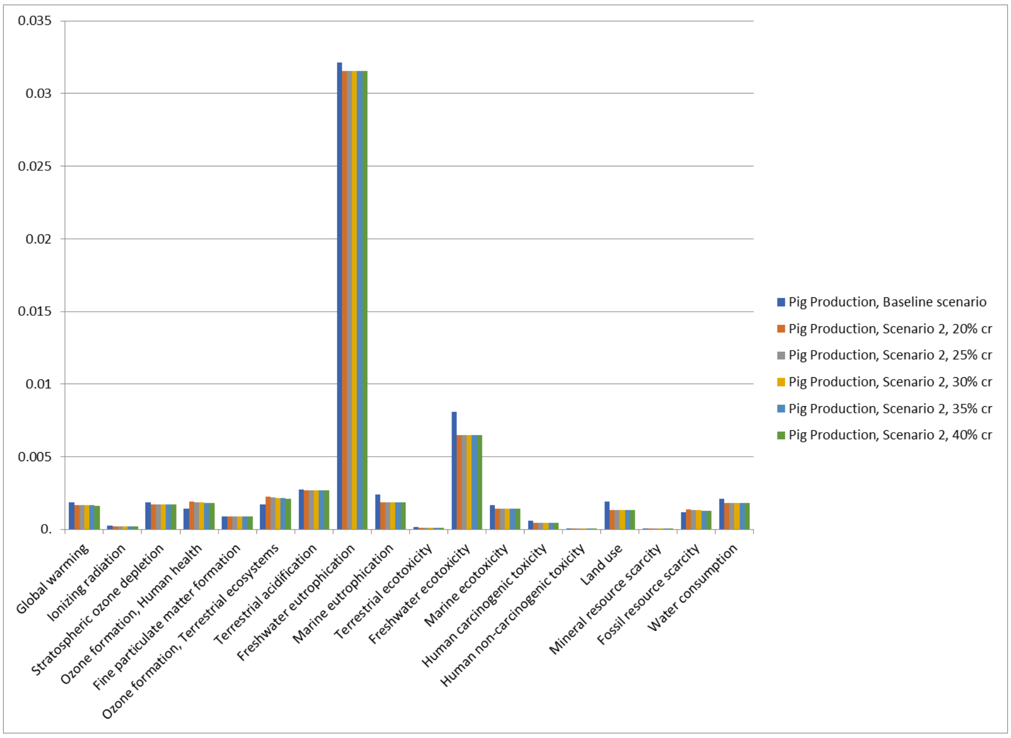

Figure A6. Comparing Scenario 2 with 20%, 25%, 30%, 35%, and 40% BFF to BM conversion rate to baseline scenario; method: ReCiPe 2016 Midpoint (H) V1.08/World (2010) H/Normalization.

Table A4. Land use inventory outputs with 3% cut-off.

No	Substance	Compartment	Unit	Total
	Total of all compartments		m^2a crop eq	11.79
	Remaining substances		m^2a crop eq	0.55
1	Occupation, annual crop	Raw	m^2a crop eq	5.34
2	Occupation, annual crop, non-irrigated, intensive	Raw	m^2a crop eq	2.4
3	Transformation, from forest, primary (non-use)	Raw	m^2a crop eq	1.33
4	Occupation, agriculture	Raw	m^2a crop eq	0.67
5	Transformation, from forest, unspecified	Raw	m^2a crop eq	0.65
6	Occupation, annual crop, non-irrigated	Raw	m^2a crop eq	0.44
7	Transformation, from forest, secondary (non-use)	Raw	m^2a crop eq	0.41

Table A5. Marine eutrophication inventory outputs with 3% cut-off.

No	Substance	Compartment	Unit	Total
	Total of all compartments		kg N eq	0.01
	Remaining substances		kg N eq	2.47×10^{-5}
1	Nitrate	Water	kg N eq	0.01

Table A6. Human carcinogenic toxicity inventory outputs with 3% cut-off.

No	Substance	Compartment	Unit	Total
	Total of all compartments		kg 1,4-DCB	0.2
	Remaining substances		kg 1,4-DCB	0.05
1	Chlorpyrifos	Soil	kg 1,4-DCB	0.06
2	Metolachlor, (S)	Soil	kg 1,4-DCB	0.05
3	Diflubenzuron	Soil	kg 1,4-DCB	0.04
4	Vanadium	Water	kg 1,4-DCB	0.01

Table A7. Ozone formation, human health inventory outputs with 3% cut-off.

No	Substance	Compartment	Unit	Total
	Total of all compartments		kg NOx eq	0.04
	Remaining substances		kg NOx eq	1.06×10^{-3}
1	Nitrogen oxides	Air	kg NOx eq	0.03
2	Nitrogen dioxide	Air	kg NOx eq	1.8×10^{-3}

Table A8. Ozone formation, terrestrial ecosystem inventory outputs with 3% cut-off.

No	Substance	Compartment	Unit	Total
	Total of all compartments		kg NOx eq	0.04
	Remaining substances		kg NOx eq	1.53×10^{-3}
1	Nitrogen oxides	Air	kg NOx eq	0.03
2	Nitrogen dioxide	Air	kg NOx eq	1.8×10^{-3}

Table A9. Human non-carcinogenic toxicity inventory outputs with 3% cut-off.

No	Substance	Compartment	Unit	Total
	Total of all compartments		kg 1,4-DCB	0.36
	Remaining substances		kg 1,4-DCB	0.06
1	Acephate	Soil	kg 1,4-DCB	0.14
2	Barium (II)	Water	kg 1,4-DCB	0.12
3	Vanadium	Water	kg 1,4-DCB	0.03
4	Arsenic, ion	Water	kg 1,4-DCB	0.01

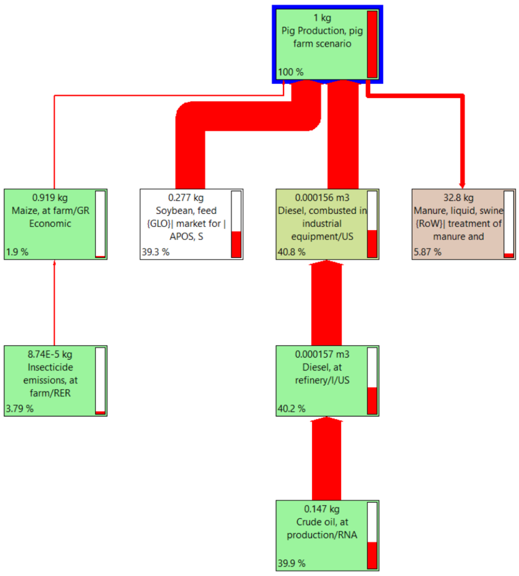

Figure A7. Human non-carcinogenic contribution by process in network view.

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