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# Environmental Impact Assessment of Sustainable Pig Farm via Management of Nutrient and Co-Product Flows in the Farm

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**Abstract:** This study evaluates the environmental impact assessment of sustainable pig farm via management of nutrient and co-product flows in the farm. Manure management and biogas production are among the most promising pathways towards fully utilizing organic waste within a circular bioeconomy as the most environmentally friendly solution mitigating gaseous emissions and producing bioenergy and high-quality bio-fertilizers. The concept of farm management includes rearing pig, growing all the feeds needed, and managing the nutrients and co-product flows in the farm. A consequential life cycle assessment (LCA) was performed to examine three scenarios in which all the generated manure is used as fertilizer for barley cultivation and mineral fertilizer is used where necessary (SC1); produced surplus straw is used for thermal energy generation and maize is used for sale, substituting maize biomass in the market (SC2); and all co-products are circulated in a closed system (SC3). The functional unit (FU) was defined as a "farm with 1000 fattening pigs at farm gate". The analysis showed that heat generation from wheat, barley and legumes straw has a significantly higher positive environmental impact than the use of these cereal straw for biogas production. The partial replacement of mineral fertilizers with digestate has positive environmental effects in terms of abiotic depletion, photochemical oxidation, terrestrial ecotoxicity, freshwater aquatic ecotoxicity, human toxicity, and marine aquatic ecotoxic aspects. The amount of digestate generated on a farm is not sufficient to completely eliminate the use of mineral fertilizers for plant fertilization. The generated pig manure (SC1) and digestate (SC2) is only enough for the fertilization of 8.3% of the total cultivated land of farm applying 22.9 t/ha rate.

**Keywords:** energy crops; pig farming; productivity; energy potential; GHG emissions; LCA; slurry

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## 1. Introduction

Many countries in the world are facing the challenge of increasing waste and improving their recycling efficiencies. Effective production systems should be established to meet increasing human needs and at the same time optimized for environmental efficiency [1].

Pig production has increased during the last decade [2] and continues to increase. Pig supply chains are estimated to produce 0.7 Gt $CO_2$ eq per annum with the average GHG emission intensity of 6.1 kg $CO_2$ eq per kg of meat [3]. Feed production contributes 60% of the emissions arising from global pig supply chains, and manure storage/processing 27%. The remaining 13% arises from a combination of post-farm processing and the transport of meat. $N_2O$ resulting from the application of synthetic and organic fertilizers in feed crop production accounts for 17% of total pig emissions, while $CO_2$ from the use of energy in field operations, crop transport and processing, and the manufacture of fertilizer and synthetic feed materials accounts for 27% [3]. On-farm energy consumption represents only 3.5% of emissions. On a global scale, intensive large-scale systems account for most of both total production and emissions. Backyard systems have relatively high manure emissions, caused by larger amounts of volatile solids and N excretion per kg of meat produced. Higher manure emissions in backyard systems are controlled by relatively low emissions from feed, as the provision of low-quality feed has low emissions [3]. Recovering heat waste and using the digestate as fertilizers would improve the environmental sustainability of a farm containing biogas plant [4,5].

The importance of nitrogen (N) across different sectors has been established over the years, especially in the agricultural sector. One of the highlighted historical needs for reactive nitrogen is to provide fertilizers to increase food production [6]. Food production and livestock production have increased via the contribution of N sources to meet the demand of the human population. However, the usefulness of N has come at a huge cost as supply has increased more than the demand (consumption), hence creating an imbalance in the N cycle. The tilt in the N imbalance has recently been receiving the attention it deserves to ensure that N sources are efficiently and sustainably managed in a circular economy. Intensive agricultural production is highly dependent on the effective recycling of nitrogen, made possible by the use of organic and inorganic fertilizers which are ready sources of N and which are needed for the productivity of crops and soil [7]. With these in perspective, the next step of integration in the N flow is that of nutrient management. The excessive application of N inadvertently leads to poor water quality resulting from algae boom and low oxygen level concentration, air quality, greenhouse balance, and ecosystems soil quality (inorganic N acidification) [8–10]. The application of the digestate products to agricultural fields has received a significant boost in recent years due to the drive for organic farming, improved crop yield, enhanced soil health [11], and increased soil biodiversity when compared to inorganic fertilizers [12–14]. The application of digestate derived from pig farm co-products provides a win–win in pollution control and agricultural use as effective management would help channel N sources to meet N demands by crops and soil for uptake and utilization. Secondly, the act of making result-driven decisions to assess and continuously monitor the impacts and selection of the best agronomic and environmental targets for N management is deemed necessary. This would lead to a better execution of the management plan that would involve evaluating and the control of the input–output N balance sheet, the collection of data on yield and N contents all aimed at minimising the N loss. Hence, focusing on understanding the nitrogen flow while maximising their useability will inform policy development for sustainable nitrogen management.

In agriculture, one of the most effective uses of waste and non-food crops in this area is anaerobic digestion—biogas production. In this process, biomass is recycled, biogas is produced and the secondary product—digestate is generated. Biogas can be used as a renewable energy source for heat and electricity or for transportation fuel. According to its chemical composition, it is likely that digestate is a suitable organic fertilizer for agricultural crops and could contribute both to increasing the efficiency of biogas and to the increase in the economic efficiency of agriculture and the use of wasteless technologies in agriculture [4]. Biogas production is one of the most promising avenues for fully utilizing organic waste within a circular economy [15]. The anaerobic digestion of manure has been suggested as the most environmentally friendly solution mitigating methane ($CH_4$) and ammonia ($NH_3$) emissions and producing bioenergy and high-quality bio-fertilizers [16]. The use of digestate for fertilizing agricultural crops as well as the biogas production process has deep historical origins. In the 13th century, the anaerobic digestion of manure began in China when local people found that manure processed in anaerobic digesters is more suitable for plant fertilization than fresh manure because it does not burn the roots of plants [17–19]. The targeted and effective use of bio-substrate contributes to the economic efficiency of the biogas production process [20]. In the anaerobic process, organic matter is mineralized into water-soluble compounds that can easily be absorbed by plants [21]. In the biogas production process, most of the organic nitrogen is converted into ammonia nitrogen, which is more accessible to plant roots than other nitrogen compounds or by nitrifying the bacteria/fungi processed into nitrates [22,23].

The environmental impact assessment makes it possible to compare the environmental impact of the raw materials, energy, and co-products processing cycles [5]. This approach is widely used to assess the technological processes from an environmental point of view throughout their life cycle [24]. The environmental impact assessment of the entire sustainable pig farm as a single complex process was performed based on the life cycle assessment (LCA) methodology [25]. Specific environmental impact categories are usually considered to assess the environmental impact of a process, which are related to the use of resources, the emissions of environmentally harmful substances (such as greenhouse gases), which can also affect human health [26,27]. Environmental impact assessment methods shall use models to quantify the causal links between the materials, energy inputs and emissions associated with the biomass preparation, processing, and farm maintenance cycle and with each environmental impact category considered [28]. The LCA study included all steps of sustainable pig farming: feed production, crop and biomass cultivation, pig rearing, slurry treatment, biogas production, transportation, and the application of produced organic fertilizers and surplus grains or straw, to prevent the production, transportation, and application of replaced mineral fertilizers including emissions from the treatment and fertilizer application.

The objective of this investigation was to evaluate the environmental performance of a pig farm as a single unit with different scenarios of nutrient and co-product flows.

## 2. Materials and Methods

### *2.1. Description of the System Analysed*

The scope of the assessment includes the environmental impact in the whole cycle of the pig farm operation under different scenarios based on different fertilization rates and types, and surplus biomass usage in other systems as suggested by [29]. The aforementioned study investigated four slurry management options that would enable N and P to be exported from a pig-producing farm ('donor' farm) to a farm with the capacity to utilise slurry products for crop production ('recipient' farm) and the anaerobic digestion of the slurry without the export of slurry products was included as an additional option. Similarly to the study of [30], our analysis was performed through a cradle-to-farm gate perspective, as suggested by [31]. Here, further stages of slaughtering, packaging, distribution, and meat consumption were excluded from the assessment.

Three scenarios of pig farm management were considered.

To assess the environmental impact of a pig farm during the various supply chain stages and the exploitation of resources throughout its life cycle, we used an LCA method according to ISO standards [25], in which the life cycle assessment consists of four interrelated stages: the definition of the objectives and scope of the research, inventory analysis, impact assessment, and an interpretation of the results. The assessment was performed with SimaPro 9.2 software, which simplifies the developed virtual model, sets the energy level and the corresponding potential impact on the environment. The CML-I baseline model [32] was chosen because it is widely used in LCA studies [33]. LCA was undertaken across 11 environmental impact categories based on global warming (GWP), eutrophication (EP), acidification (AP), ozone layer depletion (ODP), abiotic depletion (AD), photochemical oxidation (PO), terrestrial ecotoxicity (TE), freshwater aquatic ecotoxicity (FWAE), human toxicity (HT), abiotic depletion (fossil fuels) (ADF), marine aquatic ecotoxicity (MAE). Data on feed production, biomass and crop cultivation, transport, fertilization and other equipment were used from the Ecoinvent v3 database [34].

The schematic diagram covering the analysed farm system is shown in Figure 1. The system studied included environmental impacts related to infrastructure and equipment needed for pig farm system.

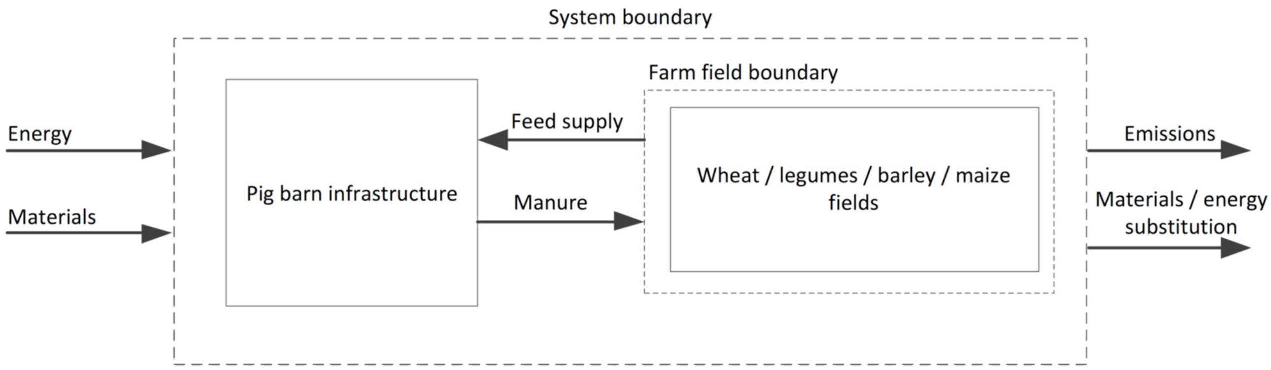



**Figure 1.** Schematic diagram of the analysed farm system.

The assessment was carried out using a four-field farming system (4 fields of 276 ha each) which would ensure the needs of 1790 t of fodder per year (more details and explanations are given in Section 2.2). The crop rotation was selected according to the need for safer crop production and an improvement in soil quality. The key points were including legumes and ensuring that the same crop would come back to the field every 4 years.

### *2.2. Functional Unit, System Boundary and the Environmental Impact Categories*

#### 2.2.1. Scope of System

Three pig farm scenarios were analysed in order to reflect the differences in the farm management systems, where a reference situation, or "baseline scenario", when all generated manure was used as fertilizer for barley cultivation and mineral fertilizer was used where necessary Scenario 1 (SC1); was supplemented with a system where produced surplus straw and crops were used for energy generation and for sale, substituting other crops in the market (SC2); and with a system where all side-streams were circulated in a closed system (SC3).

#### 2.2.2. Scenario 1 (SC1)

Scenario 1 (SC1) is a reference situation, or "baseline scenario". All generated manure is used as fertilizer for barley cultivation and mineral fertilizer is used where necessary. The analysed farm uses landless pig farming; thus, no bedding is used. The need for organic fertilizers has been calculated on the assumption that the N concentration in manure is 0.3%; therefore, 91.5 ha of barley can be fertilized with the amount of manure generated on the farm. Other barley, wheat and maize are fertilized with mineral nitrogen fertilizers 70, 103 and 150 kg N/ha, respectively. As it is not enough organic fertilizer for all crops, it was decided that barley fertilization with organic fertilizer will have the highest effect on rotation in the future. Annually, 2100 tons of liquid manure are produced by 1000 pigs, which was calculated based on [35] (Table 1). The assumption was developed that 1000 pigs are reared on the farm, 50% of pigs are 30–60 kg live weight and 50% are 60–100 kg live weight. Feed composition and consumption for pig rearing is given in Table 2. Barley, wheat and pea flour are produced on the farm from grown crops. The other feed materials are purchased from the market.

**Table 1.** On-farm liquid manure generation.

| Indicator | 30–60 kg Live Weight Pigs | 60–100 kg Live Weight Pigs |
|---|---|---|
| Liquid manure generation per pig, kg/day | 5.0 | 6.5 |
| Totally manure kg/day | 5750.0 | |
| Totally manure t/year | 2098.8 | |

**Table 2.** Feed composition and consumption for pig rearing.

| Indicator | Feed Composition, % | | Totally per Year, t |
|---|---|---|---|
| **Live Weight** | **30–60 kg** | **60–100 kg** | |
| Barley flour | 27.9 | 32.5 | 602.0 |
| Wheat flour | 27.6 | 32.3 | 597.2 |
| Pea flour | 30.0 | 30.0 | 591.3 |
| Sunflower meal | 5.0 | 0.0 | 42.0 |
| Rapeseed cake | 4.2 | 2.0 | 57.9 |
| Fish meal | 1.5 | 0.0 | 12.6 |
| Dicalcium phosphate | 0.8 | 1.1 | 19.2 |
| Feed chalk | 1.0 | 0.9 | 18.6 |
| Premix (vitamin complex) | 1.0 | 1.0 | 19.7 |
| Table salt (NaCl) | 1.0 | 0.2 | 10.7 |
| Totally | 100 | 100 | 1971.2 |

According to the feed ration, it is assumed that 276 ha of peas (with a yield of 2.14 t/ha), 183 ha of barley (with a yield of 3.29 t/ha) and 132 ha of wheat (with a yield of 4.53 t/ha) need to be grown. The land area requirement for rearing 1000 pigs on a farm and the yearly surplus feedstock for substituting crops on the market are given in Table 3. The data on crop yield were taken from Official Statistics Portal of Lithuania [36]. It was planned that all crops are grown under conventional tillage. Maize is grown in one field (276 ha) for sale substituting maize silage biomass in the market (moisture content 72% [34]). The surplus wheat (standard humidity 14%) and barley (standard humidity 14%) produced on the farm are intended for sale (replaces cereals on the market).

**Table 3.** Land area requirement for rearing 1000 pigs on a farm.

| Plant Type | Yield, t/ha | Yearly Consumption for Feed, t | Yearly Surplus Feedstock for Substituting Crops on Market, t | Land Area Requirement to Meet Farm Needs, ha |
|---|---|---|---|---|
| Barley | 3.29 | 602 | 306 | 183 |
| Wheat | 4.53 | 597 | 652 | 132 |
| Pea | 2.14 | 591 | 0 | 276 |
| Maize | 27.35 | - | 7549 | 276 |

Schematic representation of the main processes and pathways considered for the pig farm is depicted in Figure 2. Cereal straw is a co-product is used for energy production by combustion (replacing thermal energy from natural gas). A similar method, whereby the resulting by-products or surpluses replace conventional products on the market, has been used by other researchers [37,38].

#### 2.2.3. Scenario 2 (SC2)

A biogas plant is incorporated to solely treat pig manure (Figure 3). Produced biogas substitutes biogas in the market generated from pig manure. The anaerobic digestion of manure includes pig manure transportation (3 km) to the biogas plant, anaerobic fermentation, and the storage of digestate after fermentation. The digestate is applied to farm fields as fertilizer and using mineral fertilizer is avoided if possible. In this scenario, the farm replaces the purchased mineral nitrogen fertilizers by the digestate produced on farm from pig manure. The mineral fertilizer equivalent for N derived from an organic fertilizer is 75% [30] following that every 100 kg of N applied as pig manure or digestate should replace 75 kg of N from mineral fertilizers. The mineral fertilizer equivalent values for P and K in manure or digestate are considered 100% in most cases [30,39]. The quantity of generated digestate is 97.1% from input manure quantity, as having 24.3 L/kg biogas yield from pig manure and 0.040 kg/m$^3$ biogas water vapour, the mass loss is 60,651 kg. Therefore, the digestate for fertilization is 2038 tons, which was used for modelling fertilization.

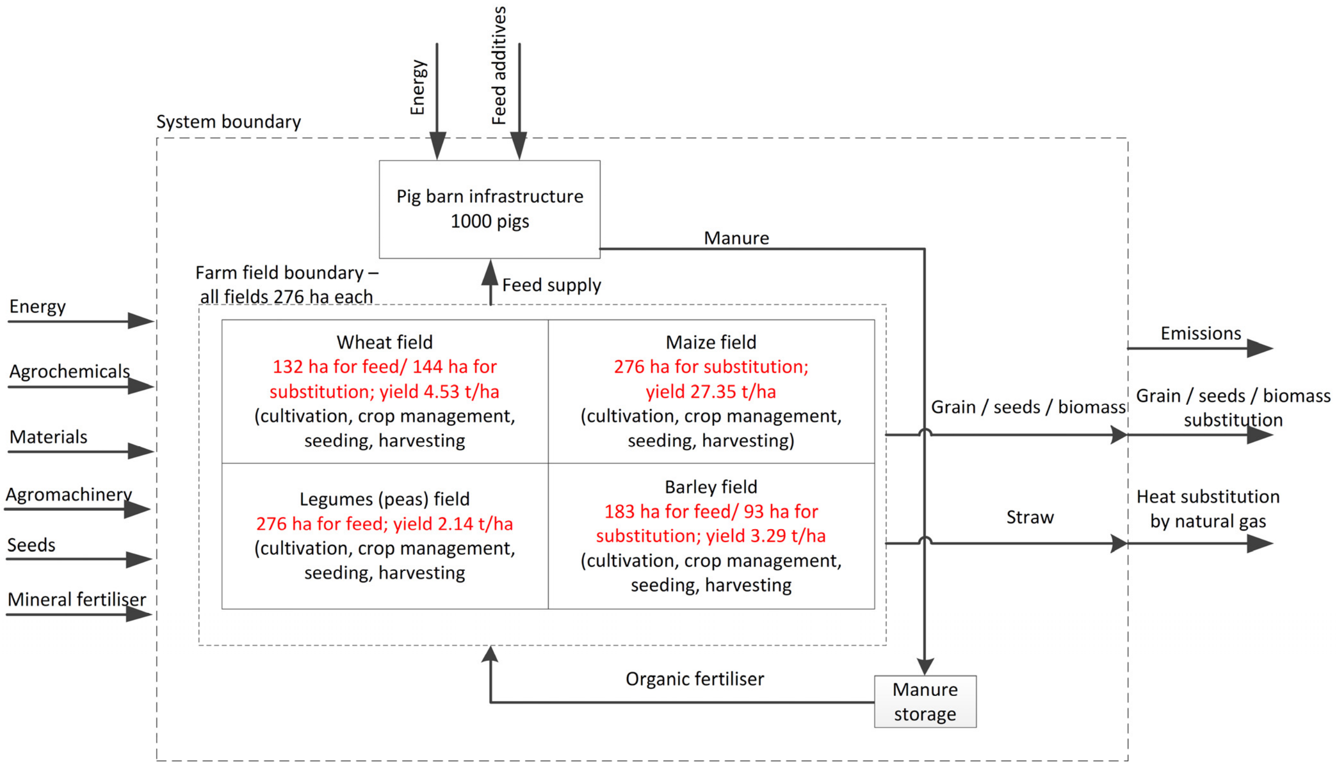



**Figure 2.** Schematic representation of the main processes and pathways considered for the pig farm in CS1.

### 2.2.4. Scenario 3 (SC3)

SC3 is the most complicated system, in which all co-products circulate in a closed system (Figure 4). The produced surplus straw and all grown maize biomass are co-digested with pig manure in the biogas plant. The digestate is used on farm fields as fertilizer and avoids mineral fertilizer. The farm replaces purchased mineral nitrogen fertilizers by digestate produced on the farm from pig manure, straw and maize co-digestion. The need for organic fertilizers was calculated on the assumption that the N concentration in digestate is 0.3%; therefore, 276 ha of barley and 181 ha of wheat can be fertilized with the amount of digestate (12,739 t) generated on the farm. The rest fields are fertilized by mineral nitrogen fertilizers. The average crop straw total solids (TS) concentration is assumed to be 90% [40]. The silage of maize contains 25% TS [41]. Digestate has a lower TS content than the undigested feedstock. It is suggested that at least 50–90% of the TS content is converted to biogas [42–44], and thus the substrate liquifies. Assuming the straw and maize silage TS biodegradation ratio of 60% and that of pig manure being 50%, the calculated TS concentration in the anaerobic digester is 15%, which is favourable for liquid completely stirred digesters [45,46].

Biogas yield from maize silage (at 25% TS) was assumed to be 156 L/kg, from wheat straw (at 90% TS)—370 L/kg [47], from barley straw (at 90% TS)—544 L/kg [48] and from pea straw (at 90% TS)—317 L/kg [49].

### 2.2.5. Functional Unit

The functional unit of the pig farm system was selected for a comparison of the scenarios of the whole pig farm cycle. The functional unit (FU) was defined as the "farm with 1000 fattening pigs at farm gate".

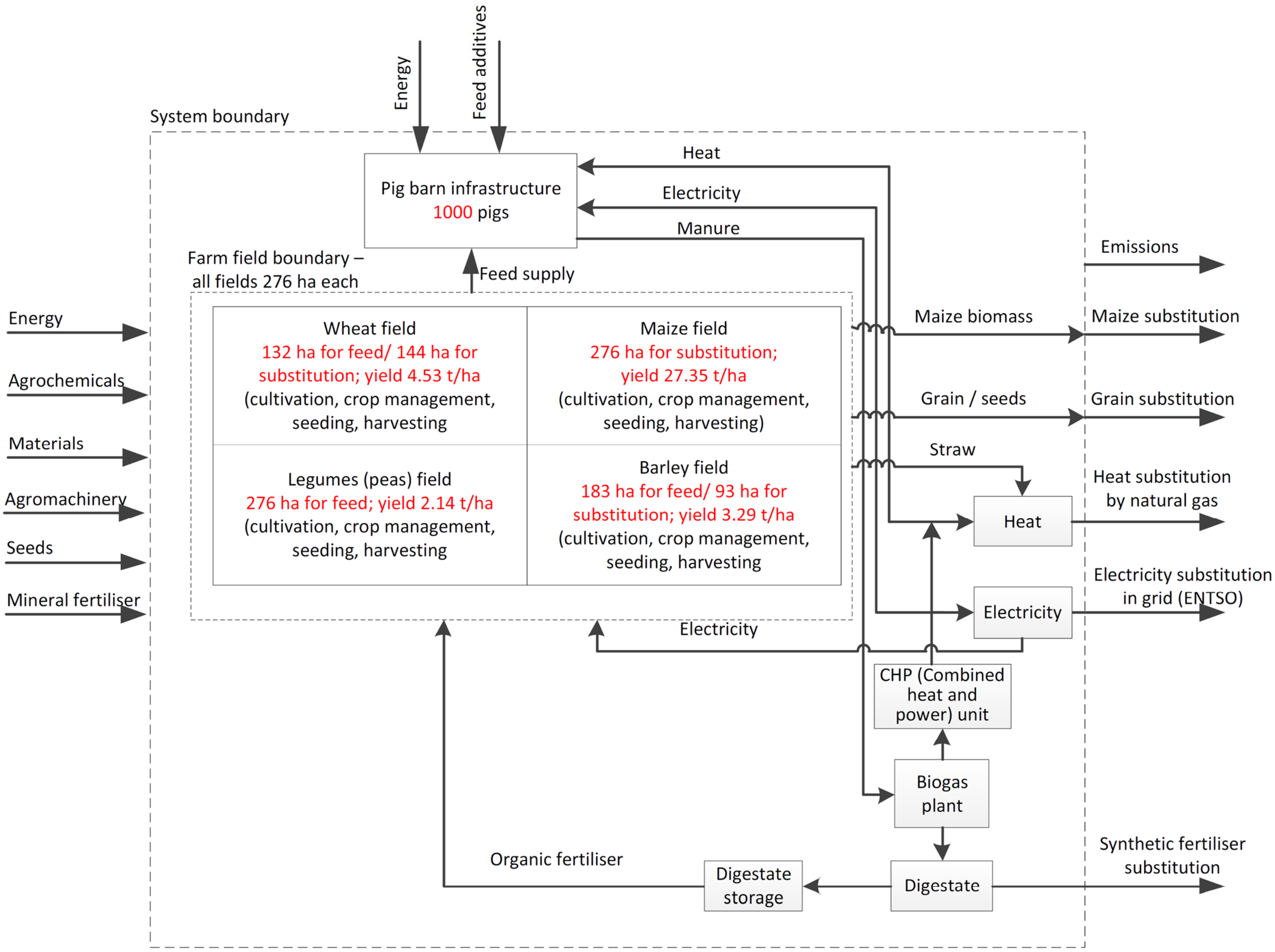



**Figure 3.** Schematic representation of the main processes and pathways considered for the pig farm in CS2.

### 2.3. Allocation Procedures

In general, a common methodological decision in LCA occurs when the system being studied produces co-products. When more co-products are created from the analysed process, less environmental impact will be allocated to the process. The co-products linked to the pig farm systems are substituted for other products on the market, such as surplus grain, heat and electricity [50]. Thus, the boundaries of the analysed system must be widened to include the system using all the co-products [51]. In the analysed system, the pigs after the fattening stage and surplus crops were as the main products which have an important commercial value. The manure from pigs and straw can be also considered as valuable co-products. The ISO standard [25] recommends avoiding allocation by expanding the assessed system. Following the recommendation, pig manure, digestate, straw and surplus crops were assumed to substitute mineral fertilizers and heat generation from the fossil fuels and crops in existing markets or other farms. The credits related to the production and further application of avoided products was assigned to the reduction in environmental loads, and thereby contributing with a negative number of emissions [52,53] and a lower consumption of energy [54]. Manure negatively affects the environment because it causes emissions of ammonia, nitrous oxide, nitrate and phosphate, both during storage and when the manure is applied as fertilizer to field-grown crops [55]. In an integrated farming system where manure is recycled to feed crops only, it does not matter whether manure emissions are allocated to the pigs or the feed crops, since the environmental burden will be allocated to the pigs in any case. The calculation of the emissions from the stable, storage and field was based on [55]. The digestate can be used as fertilizer on agricultural land. The digestate contains active fertilizer ingredients of superphosphate ($P_2O_5$), potassium chloride ($K_2O$) and ammonium nitrate ($NH_4$-N) fertilizers. The quantity of mineral fertilizers substituted was defined considering the nutrients content within the digestate. If the manure was used for biogas production, the net benefit in terms of avoided $CO_2$ emissions—and any other avoided emissions—were deducted from the environmental assessment of the pig products. Allocation by physical causality (weight or volume) was applied as suggested in [56]. It is suggested to allocate co-products in proportion to their energy content; however, using the energy value of organic fertilizer does not accurately value its nutrient content; moreover, slurry and digestate, particularly in liquid form, have a limited energy content [51]. It has been suggested that one should use a substitute approach by giving credit to the mineral fertilizer displaced by the organic fertilizer [57]. Credits for avoided fertilizer application which involved avoided manufacture were used from the Ecoinvent database [34].

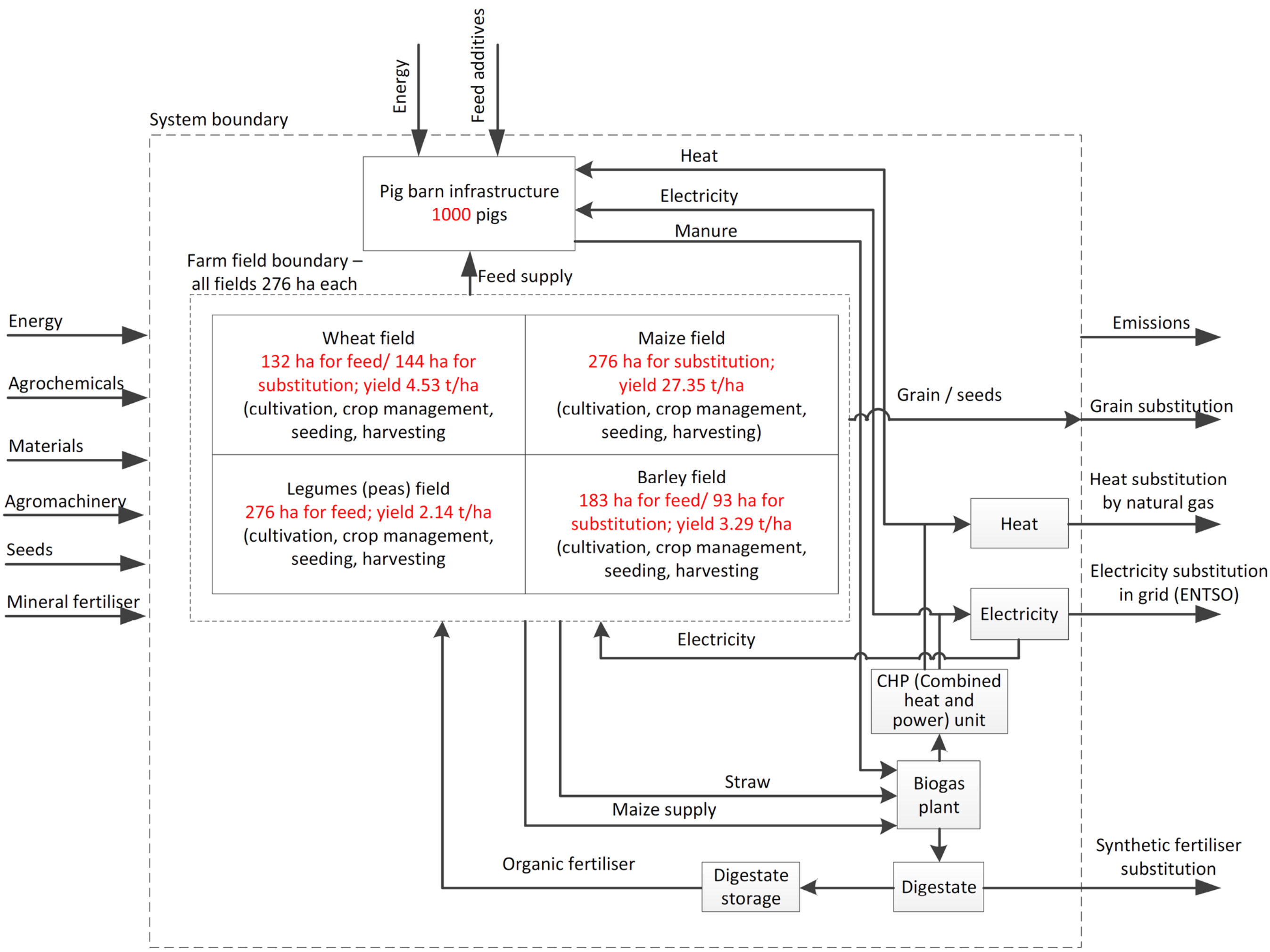



**Figure 4.** Schematic representation of the main processes and pathways considered for the pig farm in SC3.

## 3. Results

### *3.1. Energy Inputs*

The field machinery operational characteristics and energy inputs that are directly or indirectly linked with the agricultural machinery use are shown in Table 4.

**Table 4.** Field machinery operational characteristics and energy input (MJ/ha) for three scenarios.

| Operation | Operating Machinery, Implements, Power | Spring Barley | | | Spring Wheat | | | Maize | Legumes (Peas) |
|---|---|---|---|---|---|---|---|---|---|
| | | SC1 | SC2 | SC3 | SC1 | SC2 | SC3 | SC1, SC2, CS3 | SC1, SC2, CS3 |
| Units | | MJ/ha | MJ/ha | MJ/ha | MJ/ha | MJ/ha | MJ/ha | MJ/ha | MJ/ha |
| Ploughing | Tractor 120 kW + 4-share plough | 402 | 402 | 402 | 402 | 402 | 402 | 402 | 402 |
| Disc harrowing | Tractor 120 kW + Rotary Harrow 6 m | 257 | 257 | 257 | 257 | 257 | 257 | 257 | 257 |
| Transportation of mineral fertilizers | Truck 24 t, 440 kW | 11 | 11 | - | 11 | 11 | 11 | 11 | - |
| Fertilizer spreading | Tractor 78 kW + Fertilizer Spreader | 29 | 29 | - | 29 | 29 | 29 | 32 | 36 |
| Pre-sowing tillage | Case 160 AG, germinator 6 mg | 181 | 181 | 181 | 181 | 181 | 181 | 181 | 181 |
| Sowing | Tractor 78 kW; Seeder Fiona 3 m | 250 | 250 | 250 | 250 | 250 | 250 | 250 | 250 |
| Application of organic liquid fertilizers. First insertion | Case 160 AG + 8.8 $m^3$ capacity GT series slurry truck with insertion system | 367 | 367 | 367 | - | 375 | 375 | - | - |
| Spring spraying | CASE 105 AG, sprayer, 12 m | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| Application of organic liquid fertilizers. Second insertion | Case 160 AG + 8.8 $m^3$ capacity GT series slurry truck with insertion system | 367 | 367 | 367 | - | 375 | 375 | - | - |
| Spraying 1 | CASE 105 AG, sprayer, 12 m | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| Spraying 2 | CASE 105 AG, sprayer, 12 m | 60 | 60 | 60 | 60 | 60 | 60 | 60 | - |
| Spraying 3 | CASE 105 AG, sprayer, 12 m | 60 | 60 | 60 | 60 | 60 | 60 | - | - |
| Harvesting (crops) | Class Tucano, 238 AG, 5.4 m | 982 | 982 | 982 | 982 | 982 | 982 | - | 982 |
| Harvesting (maize) | Self-propelled forage harvester, 580 kW + tractor 160 kW | - | - | - | - | - | - | 470 | - |
| Transportation of organic liquid fertilizers | Tank truck MAN, 162 kW, capacity 8 $m^3$ | 884 | 884 | 884 | - | 884 | 884 | - | - |
| | Total | 3970 | 3970 | 3930 | 2352 | 3986 | 3986 | 1783 | 2228 |

The diesel energy coefficient that corresponds to the chemical energy of diesel is equal to 41.2 MJ/L. This coefficient is recommended and adopted across Europe because of the shorter distance across which crude oil is transported from the Middle East [58]. It includes the crude oil energy content, production energy consumption, shipping energy consumption, and refining/distribution energy consumption.

### 3.2. Inventory Analysis

Data are collected based on official statistics or scientific publications. According to the recommended data quality assessment methodology [59], our data indicate that the Data Quality Score is lower than three, showing a good quality level.

Table 5 summarises the life cycle inventory of the pig farm technology for SC1, SC2 and SC3 inputs and outputs, underpinning the LCA results across 11 impact categories. The comparative total energy, water and material input were calculated based on the assumption of the defined functional unit as a "farm with 1000 fattening pigs at the farm gate".

### 3.3. Environmental Indicators of Pig Farming

The environmental impact assessment of the sustainable life cycle of the entire pig farm shows that some impact categories (GWP, EP, AP) have negative indicators, some (AD, PO, TE, FWAE, HT, MAE) have positive indicators, while ODP and ADF impact categories have both positive and negative. A negative indicator characterizes emission savings. Emissions are reduced by the supplying of surplus farmed cereals and maize to the market, which avoids the production of similar products on other farms (in SC1 and SC2) and avoiding the energy generation from other sources or mineral fertilizer production (SC3).

The total annual $CO_2$ emissions of the whole farm is from −2181.7 t $CO_2$ eq (SC2) to −269.4 t $CO_2$ eq (SC3) (Table 6). The greatest environmental impact of all the considered categories occurs for SC3.

**Table 5.** Inventory of inputs and outputs for a reference flow of 1000 pig farm of three scenarios.

| Stage | Input/Output/Process | Units | SC1 | | SC2 | | SC3 | |
|---|---|---|---|---|---|---|---|---|
| | | | In | Out | In | Out | In | Out |
| Cultivation | Fuel (diesel) | kg | 231,389 | | 231,389 | | 197,252 | |
| | Nitrogen fertilizer, inorganic | kg | 55,658.4 | | 55,658.4 | | 17,732.6 | |
| | Potassium chloride as $K_2O$ | kg | 64,086.5 | | 64,086.5 | | 25,801.3 | |
| | Agrochemicals (pesticides, herbicides, fungicides) | kg | 1959.4 | | 1959.4 | | 2186.6 | |
| | Land | ha | 1104 | | 1104 | | 1104 | |
| | Electricity | MJ | 196,290 | | 196,290 | | 219,330 | |
| | Heat | MJ | 2,899,980 | | 2,899,980 | | 36,105 | |
| | Water | $m^3$ | 6714.2 | | 6714.2 | | 6714.2 | |
| | Barley | kg | | 908,040 | | 908,040 | | |
| | Barley straw | kg | | 1,089,648 | | 1,089,648 | 1,089,648 | |
| | Wheat | Kg | | 1,250,280 | | 1,250,280 | | |
| | Wheat straw | kg | | 1,625,364 | | 1,625,364 | 1,625,364 | |
| | Pea | kg | | 590,640 | | 590,640 | | |
| | Pea straw | kg | | 767,832 | | 767,832 | 767,832 | |
| | Maize | kg | | 7,548,600 | | 7,548,600 | 7,548,600 | |
| | Manure | kg | | 2,098,800 | | 2,098,800 | | 2,098,800 |
| | Digestate | kg | | | | 2,038,150 | | 12,738,651 |
| | Transportation | t·km | 218,725 | | 225,668 | | 257,597 | |
| | Agricultural machinery | kg | 7334.3 | | 7448.2 | | 2941 | |
| Substituted products | Substituted wheat grain | kg | −652,000 | | −652,000 | | −652,000 | |
| | Substituted barley grain | kg | −306,000 | | −306,000 | | −306,000 | |
| | Substituted maize silage | kg | −7,548,600 | | −7,548,600 | | 0 | |
| | Substituted ammonium nitrate | kg | −6405 | | −6405 | | −122,207 | |
| | Substituted heat | GJ | −146,847 | | −146,849 | | −4657 | |
| | Avoided diesel | kg | −4310 | | −4310 | | −13,340 | |

**Table 6.** Summary results per functional unit (farm with 1000 fattening pigs at farm gate) management.

| Impact Category | Unit | SC1 | SC2 | SC3 |
|---|---|---|---|---|
| Global warming (GWP100a) | kg $CO_2$ eq | −2,127,937 | −2,181,688 | −269,389 |
| Eutrophication | kg $PO_4$ eq | −13,775 | −13,894 | −9105 |
| Acidification | kg $SO_2$ eq | −13,388 | −13,703 | −8269 |
| Ozone layer depletion (ODP) | kg CFC-11 eq | −0.253 | −0.257 | 0.0584 |
| Abiotic depletion | kg Sb eq | 21.7 | 20.8 | 13.0 |
| Photochemical oxidation | kg $C_2H_4$ eq | 92.3 | 80.7 | 67.4 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 4709 | 4424 | 4160 |
| Fresh water aquatic ecotoxicity | kg 1,4-DB eq | 605,735 | 574,248 | 378,655 |
| Human toxicity | kg 1,4-DB eq | 853,425 | 809,332 | 539,232 |
| Abiotic depletion (fossil fuels) | MJ | −31,809,456 | −32,364,697 | 5,934,459 |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 1,257,615,704 | 1,187,382,468 | 755,845,079 |

All 11 environmental impact categories were evaluated (Figure 5) and the largest differences between the studied scenarios were found in the GWP, ODP, and ADF categories. Therefore, it will be mainly these categories that will be discussed.

The amount of generated digestate is not sufficient (SC3, SC2) to eliminate the use of mineral fertilizers on the farm. The generated pig manure (SC1) and digestate (SC2) are enough for the fertilization of 91.5 ha of barley applying a 22.9 t/ha rate. SC3 generates more digestate from pig manure, straw and maize, thus applying 22.9 t/ha for barley and 34.3 t/ha for wheat, it is possible to fertilize 457 ha of crops (276 ha of barley and 181 ha of wheat). However, the partial replacement of mineral fertilizers with digestate has positive environmental effects in terms of AD, PO, TE, FWAE, HT, MAE aspects (Figure 5, SC3). Additionally, in the case of SC2, removing straw from the field reduces carbon sequestration in the soil, limiting the availability of soil nutrients. Additionally, this leads to a greater need for the use of compensatory mineral fertilizers [60,61]. Therefore, the replacement of some mineral fertilizers with digestate may help compensate for most of the potential effects of GWP, EP, AP, AD and ODP (Figure 5, SC2). Assessing the GWP for each process separately, it was found that processes such as wheat cultivation with mineral fertilizers, maize cultivation and legumes cultivation have the greatest negative impact on the global worming potential (Figure 6). A comparison of barley and wheat fertilization with digestate and fertilization with mineral fertilizers showed a lower negative effect on the environment for barley and wheat cultivation with digestate (SC3), −43,015 and −200,452 kg $CO_2$ eq, respectively. The evaluation was performed by summing up the results of barley and wheat fertilization with digestate and fertilization with mineral fertilizers.

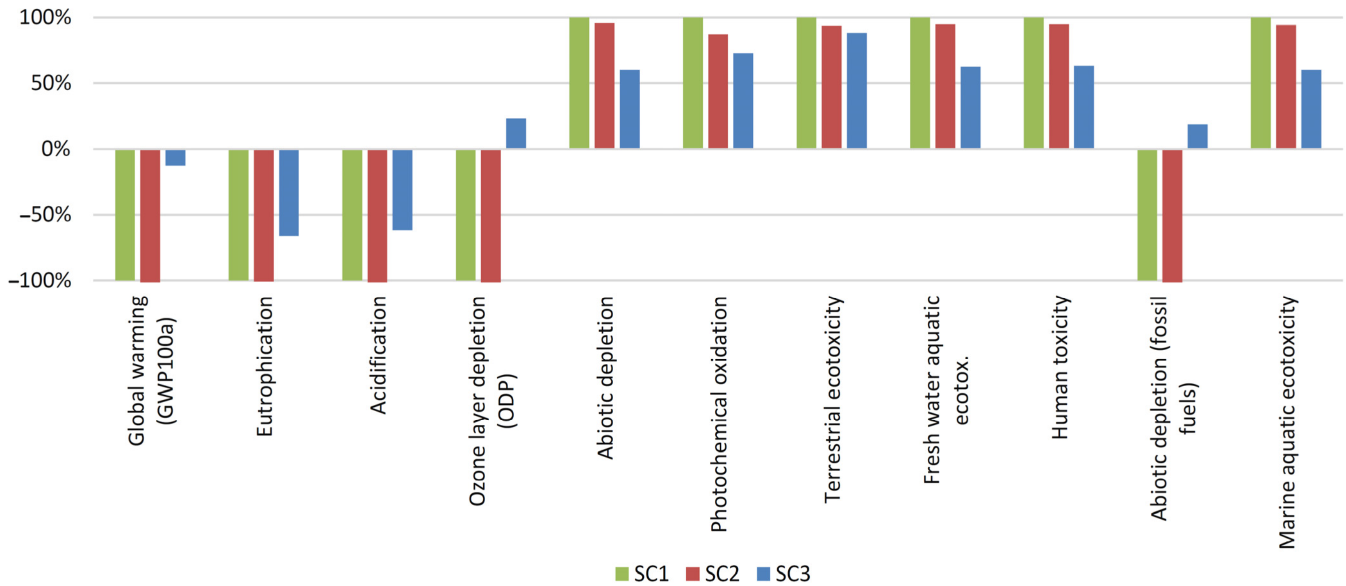
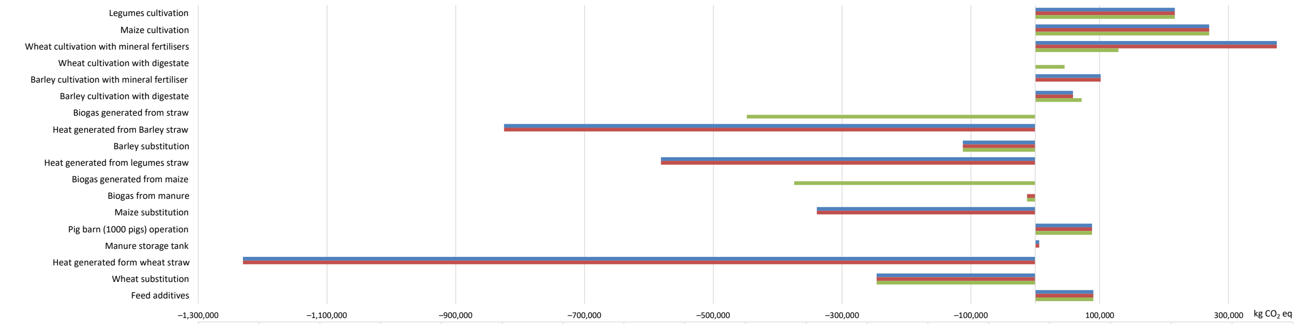



**Figure 5.** Environmental impact assessment diagrams for three compared systems. The x-axis shows the impact categories and the percentage of 100% impact for the scenario that generates the greatest impact within each category.

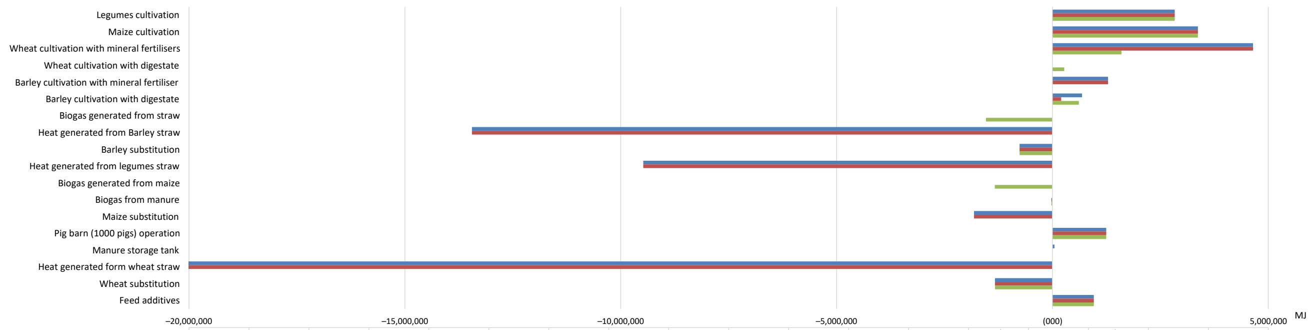
According to [61], the conversion of straw to heat increases the effect of eutrophication and acidification compared to natural gas, as it is related to the use of compensatory mineral fertilizers. Replacing some mineral fertilizers with digestate can help offset much of the potential effects of GWP, AD and PO.

Pardo et al. (2017) [62] reported that the use of maize improved the efficiency of the anaerobic digestion process, but their cultivation for energy purposes was associated with a significant environmental burden related to energy and fertilizer consumption, as well as indirect land use change. The results of these studies revealed that biogas production from maize is a more sustainable solution from an environmental point of view of the GWP category (−374,434 $CO_2$ eq) than replacing maize on the market (−339,272 $CO_2$ eq) (Figure 6). However, considering other impact categories (abiotic depletion fossil fuel and ozone layer depletion) (Figures 7 and 8), maize substitution has a greater environmental impact than biogas production. Fifty-six percent of the total impact is linked to greenhouse gas emissions related to activities associated with previous processes (pressing and loading, shredding and transportation). It is estimated that 40% of the total impact is related to the transport process, followed by combined processes: pressing and loading (15%) and the rest to the chopping of residues. Downstream electricity, particularly for primary combustion, is estimated to cover 29% (i.e., 1.23 g $CO_2$-eq/MJ heat) of total GWP. The energy stored in biomass can be converted into heat by biomass combustion, pyrolysis or gasification. Theoretical conversion efficiencies and process conditions often differ from those achieved in practice due to commercial constraints and raw material variability [63]. However, the results of wheat and barley substitution are identical in all scenarios (−246,427 and −112,537 kg $CO_2$ eq, respectively). The use of maize for biogas production has a higher positive environmental effect (SC3) compared to the substitution of maize (SC1, SC2)—−339,272 kg $CO_2$ eq.




| | Feed additives | Wheat substitution | Heat generated form wheat straw | Manure storage tank | Pig barn (1000 pigs) operation | Maize substitution | Biogas from manure | Biogas generated from maize | Heat generated from legumes straw | Barley substitution | Heat generated from Barley straw | Biogas generated from straw | Barley cultivation with digestate | Barley cultivation with mineral fertiliser | Wheat cultivation with digestate | Wheat cultivation with mineral fertilisers | Maize cultivation | Legumes cultivation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SC1 | 90,285 | −246,427 | −1,230,608 | 6181 | 88,177 | −339,272 | | | −581,347 | −112,537 | −825,003 | | 58,661 | 101,676 | | 375,209 | 270,071 | 216,721 |
| SC2 | 90,285 | −246,427 | −1,230,608 | 6181 | 88,177 | −339,272 | −12,739 | | −581,347 | −112,537 | −825,003 | | 58,661 | 101,676 | | 375,209 | 270,071 | 216,721 |
| SC3 | 90,285 | −246,427 | | | 88,177 | | −12,739 | −374,434 | | −112,537 | | −448,043 | 71,945 | | 45,609 | 129,148 | 270,071 | 216,721 |

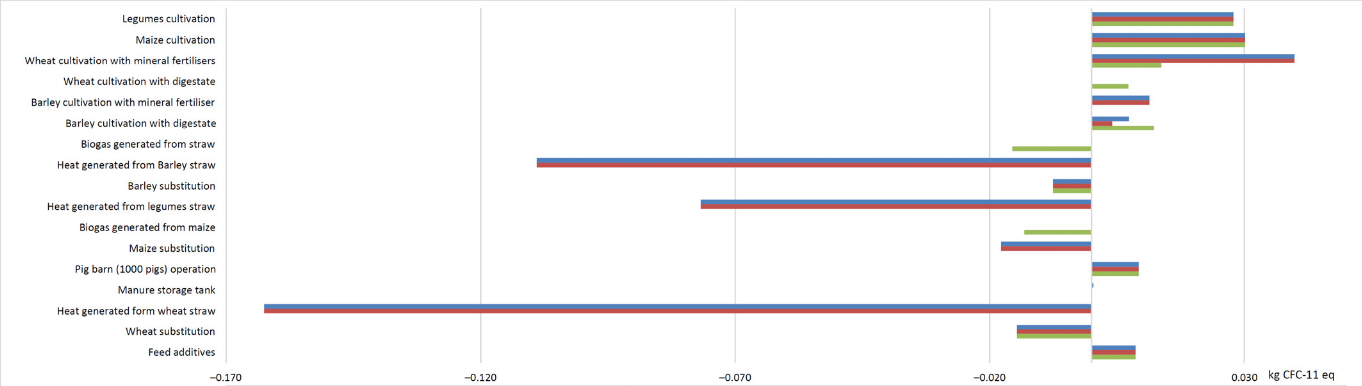
**Figure 6.** Results of processes for global warming potential.




| | Feed additives | Wheat substitution | Heat generated form wheat straw | Manure storage tank | Pig barn (1000 pigs) operation | Maize substitution | Biogas from manure | Biogas generated from maize | Heat generated from legumes straw | Barley substitution | Heat generated from Barley straw | Biogas generated from straw | Barley cultivation with digestate | Barley cultivation with mineral fertiliser | Wheat cultivation with digestate | Wheat cultivation with mineral fertilisers | Maize cultivation | Legumes cultivation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SC1 | 959,569 | −1,328,411 | −20,059,706 | 47,041 | 1,247,610 | −1,815,437 | | | −9,476,329 | −760,505 | −13,448,076 | | 687,190 | 1,288,018 | | 4,646,307 | 3,370,397 | 2,832,876 |
| SC2 | 959,569 | −1,328,411 | −20,059,706 | | 1,247,610 | −1,815,437 | −24,393 | | −9,476,329 | −760,505 | −13,448,076 | | 203,383 | 1,288,018 | | 4,646,307 | 3,370,397 | 2,832,876 |
| SC3 | 959,569 | −1,328,411 | | | 1,247,610 | | −24,393 | −1,334,158 | | −760,505 | | −1,540,441 | 613,484 | | 274,442 | 1,599,272 | 3,370,397 | 2,832,876 |

**Figure 7.** Results of processes for the abiotic depletion fossil fuel potential.

Heat generation from wheat, barley and legume straw has a significantly higher positive environmental impact than the use of cereal straw for biogas production (Figures 7 and 8). It was found that in the GWP impact category, biogas production from straw (wheat, legume, barley) has eight times less positive environmental impact than straw processing to heat energy, ADF—28 times; in the ODP category—22 times. Unsurprisingly, thermochemical processes are more efficient than biochemical/biological processes, have a faster reaction time and are excellent at converting most organic compounds, such as lignin in biomass, which is generally considered to be a non-biodegradable substance under anaerobic conditions and therefore cannot be completely degraded by biological methods during 20–30 days [63]. Therefore, based on the results of the study, it is appropriate to substitute straw on the market for the production of thermal energy from an environmental and energy point of view. Additionally, according to [61], the reduction in GWP is mainly due to the avoidance of $CO_2$ emissions that would have been possible due to the biomass decomposition process if straw had been applied to the soil alternately. Nevertheless, the soil incorporation of straw for C sequestration, especially where straw is used for bedding to improve animal welfare, play an important role at farm level. Therefore, more environmental indicators such as the activity of soil microorganisms and soil C sequestration potential should be evaluated.




| | Feed additives | Wheat substitution | Heat generated form wheat straw | Manure storage tank | Pig barn (1000 pigs) operation | Maize substitution | Biogas generated from maize | Heat generated from legumes straw | Barley substitution | Heat generated from Barley straw | Biogas generated from straw | Barley cultivation with digestate | Barley cultivation with mineral fertiliser | Wheat cultivation with digestate | Wheat cultivation with mineral fertilisers | Maize cultivation | Legumes cultivation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SC1 | 0.00867 | −0.01464 | −0.16252 | 0.00034 | 0.00926 | −0.01777 | | −0.07677 | −0.00755 | −0.10895 | | 0.00738 | 0.01136 | | 0.03988 | 0.03018 | 0.02790 |
| SC2 | 0.00867 | −0.01464 | −0.16252 | | 0.00926 | −0.01777 | | −0.07677 | −0.00755 | −0.10895 | | 0.00407 | 0.01136 | | 0.03988 | 0.03018 | 0.02790 |
| SC3 | 0.00867 | −0.01464 | | | 0.00926 | | −0.01321 | | −0.00755 | | −0.01554 | 0.01229 | | 0.00725 | 0.01373 | 0.03018 | 0.02790 |

**Figure 8.** Results of processes for ozone layer depletion potential.

It is appropriate to produce biogas from by-products such as pig manure reducing emissions, recovering energy from the manure and producing digestate, which can be used as a substitute for mineral fertilizers. The authors in [64] investigated the most appropriate way to convert biomass into bioenergy. They concluded that unlocking the energy potential of manure and straw a major opportunity to reduce greenhouse gas emissions in both the energy and agricultural sectors. The results of this study also confirmed the conclusions of these researchers—the most promising technology for manure treatment is anaerobic digestion and incineration for heat and energy recovery from straw. Incorporating on-farm bioenergy production into the system allowed GHG emissions to be offset by energy generation. In this case, energy generation from crop residues gave negative net GHG emissions [65].

Researchers [66] performed cultivation experiments on wheat (*Triticum* spp. L.) using anaerobically digested pig manure and urea. The emissions of greenhouse gases ($CO_2$, $CH_4$ and $N_2O$, and growth characteristics were monitored during this study, and the concentrations of heavy metals and pathogens were further investigated. Results indicated that the digestate used for fertilization was found to have a small effect on $CO_2$ and $CH_4$ emissions from the soil. However, digestate fertilizers significantly increased $N_2O$ emissions, which were five times higher than those used for urea fertilization, or 63 times higher compared to the control soil.

The field application of both mineral and organic fertilizers results in direct emissions into the air, soil and water [67]. Emission reductions were determined based on the avoided production and distribution of chemical fertilizers substituted by the manure or digestate. The digestate applied to the soil emits some biogenic $N_2O$ which occurs due to the release of N from organic fertilizers during periods in which vegetation is not able to take up nitrogen. Therefore, following [68,69], the $N_2O$ emission from the digestate converted to a global warming factor was on average 46.5 kg $CO_2$ eq/t digestate.

Based on the results of the study, the authors concluded that anaerobically processed pig manure is rich in nutrients, low in heavy metals and pathogens, does not affect higher $CH_4$ and $CO_2$ emissions when it is used for soil fertilization, but increases $N_2O$ emissions [66]. According to [66], the case of the SC3 scenario in the ODP category can be considered as the influence of $N_2O$ on the strongly increased negative impact. $N_2O$ emissions from agricultural sources are among the main contributors to global warming. Scientists estimate that livestock accounts for 68% of $N_2O$ gas from human activities, which has 298 times the global warming potential of a carbon dioxide [70]. N2O from soils enters the environment through direct (synthetic and organic fertilizers, manure and crop residues, and nitrogen mineralization due to organic carbon loss due to land use change) and indirect (nitrogen emissions and nitrogen leaching/run-off) [71].

## 4. Conclusions

This study aimed to provide the evaluation of environmental impacts of conventional and sustainable pig slurry management practice via the adjustment of nutrient flows in the farm. With comparative life cycle assessment modelling, the analysis showed that heat generation from wheat, barley and legume straw has a significantly higher positive environmental impact than the use of cereal straw for biogas production. The partial replacement of mineral fertilizers with digestate has positive environmental effects in terms of abiotic depletion, photochemical oxidation, terrestrial ecotoxicity, freshwater aquatic ecotoxicity, human toxicity and marine aquatic ecotoxicity. The amount of digestate generated on farm is not sufficient to completely eliminate the use of mineral fertilizers for plant fertilization. The generated pig manure (SC1) and digestate (SC2) is only enough for the fertilization of 91.5 ha of barley applying 22.9 t/ha rate. SC3 generates more digestate from pig manure, straw and maize, thus applying 22.9 t/ha for barley and 34.3 t/ha for wheat it is possible to fertilize a total of 457 ha of crops (276 ha of barley and 181 ha of wheat).

**Author Contributions:** Conceptualization, K.V. and K.N.; methodology, K.N.; software, K.V.; validation, V.T. and S.S.; investigation, M.R., K.B. (Kristina Bunevičienė), A.B. and K.B. (Karolina Barčauskaitė); writing—original draft preparation, K.V.; writing—review and editing, M.O.D.; visualization, K.V.; supervision, K.N.; project administration, V.T.; funding acquisition, V.T. All authors have read and agreed to the published version of the manuscript.

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