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Design of Indicators of Circular Economy as Instruments for the Evaluation of Sustainability and Efficiency in Wastewater from Pig Farming Industry

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Abstract: Circular economy intends to turn waste into resources that can be reintroduced into the production process, eliminating the negative externalities from it. The impact of pig manure on the environment is one of the main challenges in agriculture. The high amount of pig manure coming from the pig farming industry complicates the management of this type of effluents, leading to a serious impact on the environment, as it pollutes the soil, the water, and the air. The concept of the indicator of circular economy was introduced to evaluate the degree of approximation of the pig manure treatment process to the circular economy model. In light of this, these indicators showed the possibility of obtaining 0.97 m^3 water h^{-1}, 49.40 kg biofertilizer h^{-1}, and 5.33 m^3 biogas h^{-1} per 1 m^3 pig manure h^{-1} treated, allowing us to assess the minimization of waste generation and the efficiency of the use of resources. By applying an anaerobic digestion process to treat pig manure, reductions of water and natural gas consumptions were 47.01% and 5.33%, respectively, which leads to a reduction in emissions of 171.98 kg CO_2 h^{-1}. Consequently, pig manure can be considered as a technological nutrient that is reintroduced into the productive system, enabling the recovery of energy, water, and biofertilizer contained therein.

Keywords: circular economy; energy; indicator; pig manure; technological nutrient; wastewater

1. Introduction

Circular economy is a new development strategy aimed at the environment protection, pollution prevention, and sustainable development [1]. It is based on a conception that is either restorative or regenerative by intention and design, and whose only objective is to maximize resource efficiency and minimize waste production within the framework of economic and social sustainability [2–4].

In the circular economy model, waste is turned into resources, which are also called technological nutrients [5,6] and reintroduced into the production processes [7,8]. In this time of great transformations, the objective is to go from lineal economy, where society is based on waste production, consumption, and disposal, to the new model provided by circular economy, which is focused on the principles of the "3 Rs": reduction, reutilization, and recycling of as much waste as possible. Such waste is derived from the production and consumption processes, implementing processes with circular flows of matter and energy where the utilization of raw material and energy is carried out in numerous stages [9,10]. Consequently, under this concept of circular economy, the consumption of matter and energy, as well as the environmental degradation are minimized without limiting social or economic growth and technological progress [11].

In this regard, the water industry, and more specifically the wastewater one, has been quite revolutionary in its approach towards the circular economy model due to the importance of water in relation to human life and the energy and matter it contains [12,13]. In this way, wastewater is not considered a waste but a valuable non-conventional resource, since it contains water and nutrients, such as nitrogen, phosphorus, and organic matter [14]. The recovery of wastewater components for their reuse has economic and environmental benefits [15].

One of the most important challenges that the circular economy has to develop, which is also indicated by European Union, is the necessity of designing indicators that allow for assessing the advance obtained regarding the efficiency in terms of reduction, reutilization, and recycling of waste generated in the linear economy model. The indicators of circular economy are useful in order to determine the degree of approximation of any specific process to the circular economy model.

The impact of pig manure on the environment is one of the main challenges faced by the pig farming industry. More specifically, pig population in Spain rose to 28.3 million head in 2015. Consequently, Spain became the country with the highest pig population in the European Union for the first time, with an average pig manure production of 7 L head^{-1} day^{-1}, and a pig manure generation of 200,000 m^3 day^{-1} [16]. It can make us understand the magnitude of the problem. The high amount of pig manure coming from the pig industry complicates the management of this type of effluents, leading to a serious impact on the environment, since it pollutes the soil, the water, and the air. It also poses a risk for the human being and the local wildlife [17]. Thus, sustainable development plays an important role in pig farming industry [18].

Denmark, France, Germany, Holland, Poland, and Spain represent more than two-thirds of the total pig production in Europe (Eurostat, December 2008 survey), which directly implies high volumes of pig manure generated as a result [19]. With proper management, pig manure can be used as fertilizer in order to provide nutrients to crops and improve soil properties by means of the addition of organic matter [20].

Regarding air pollution, methane and carbon dioxide are emitted, both being greenhouse gases contributing to global warming. In addition, foul odors are produced and there is an excessive emission of ammonia into the atmosphere by means of losses through volatilization [21,22].

In addition to an excess of nitrogen, it is also possible to find an excess of assimilable forms of phosphorus and potassium, accumulation of heavy metals (Cu and Zn), and salinization [19] in the soil.

Pig manure also pollutes surface and underground waters, as its content in nitrates and phosphates can contribute to some phenomena, such as water eutrophication, which causes a decline in its quality [19,23–25].

Regarding hygienic-sanitary risks, gas emissions (sulfhydric, mercaptans, ammonia...) and the presence of pathogens could cause significant impacts on human and animal health due to direct toxicity and smelling aggression [19,26–29].

Consequently, it is necessary to develop and introduce systems of pig manure treatment before its spillage [30]. In this regard, anaerobic digestion stands as an appropriate process that has been widely used in pig manure treatment. This process is carried out by means of a biochemical process comprising of several stages and different types of microorganisms [31]. During such treatment, the complex organic matter contained in pig manure is hydrolyzed, fermented, and reduced to methane and carbon dioxide [32,33]. It is necessary to control different factors in this process, such as the influent characterization, microbial biomass, temperature, presence of inhibitors, mixing conditions, pH levels, and trace elements [34]. Thus, it should be pointed out its ability to produce renewable energy sources, such as biogas, with the subsequent reduction in the emissions of organic pollutants and greenhouse gases (GHG) [35]. In light of this, the obtaining of biogas contributes to the achievement of sustainable energy systems [6,36]. Moreover, biogas plays an important role in the decarbonization of the energy sector in Europe, which promotes that European Biogas Association (EBA) is developing a platform

to register the biogas at national level, and to remove the boundary barriers, thus encouraging the domestic market.

In this regard, the principles of Life Cycle Assessment (LCA) methodology have been followed in the literature as a basis for the environmental assessment of the impact caused by different pork production systems in Europe and outside its boundaries [37,38]. All of the environmental analyses aim at assessing GHG emissions in order to reduce the climate change related impacts as one of the main requirements for sustainable production [37,39,40]. In this sense, there is a growing need to meet the European Union Climate Action targets, which aim to reduce GHG emissions to 40% of the 1990 levels by 2030 [41]. In addition to this, the environmental evaluation within the framework of this research area also includes carbon and water footprints, which are selected as indicators of primary interest for companies in the sector [37,42].

Therefore, this study is focused on the development and evaluation of indicators of circular economy as applied to pig manure management from an environmental point of view, and as a first case of implementation in pig production, a sector of particular importance in Spain. This research could supply information of interest to companies in the sector that contributes to the development of LCA methodology and carbon and water footprints.

2. Materials and Methods

2.1. Description of the Pig Manure Treatment Plant

The pig manure treatment plant occupies a smallholding with a surface of 19,000 m^2. The anaerobic digestion plant used for pig manure treatment treats a pig manure flow rate (Q_{sw}) of 120,000 m^3 year^{-1}, for an operation time of 8000 h year^{-1}, with the characteristics shown in Table 1.

Table 1. Influent characterization of the treatment plant.

Parameter	Value
Treatment flow (m^3 year^{-1})	120,000
Q_{sw} (m^3 h^{-1})	15 (8000 h year^{-1})
Temperature (°C)	15
pH	6
Water (%)	96
Dry matter (%)	4
Electrical conductivity (μS cm^{-1})	12,140
Density (g L^{-1})	1040
COD (mg O$_2$ L^{-1})	24,000
BOD$_5$ (mg O$_2$ L^{-1})	9500
Suspended solids (mg L^{-1})	7200
Volatile solids (mg L^{-1})	6000
Phosphorus (mg L^{-1})	6000
Kjeldahl nitrogen(mg L^{-1})	9500
Potassium (mg L^{-1})	7200

The process of pig manure treatment through anaerobic digestion includes several stages, such as pig manure pretreatment, anaerobic digestion, biogas cleaning and conditioning, and digestate treatment (Figure 1).
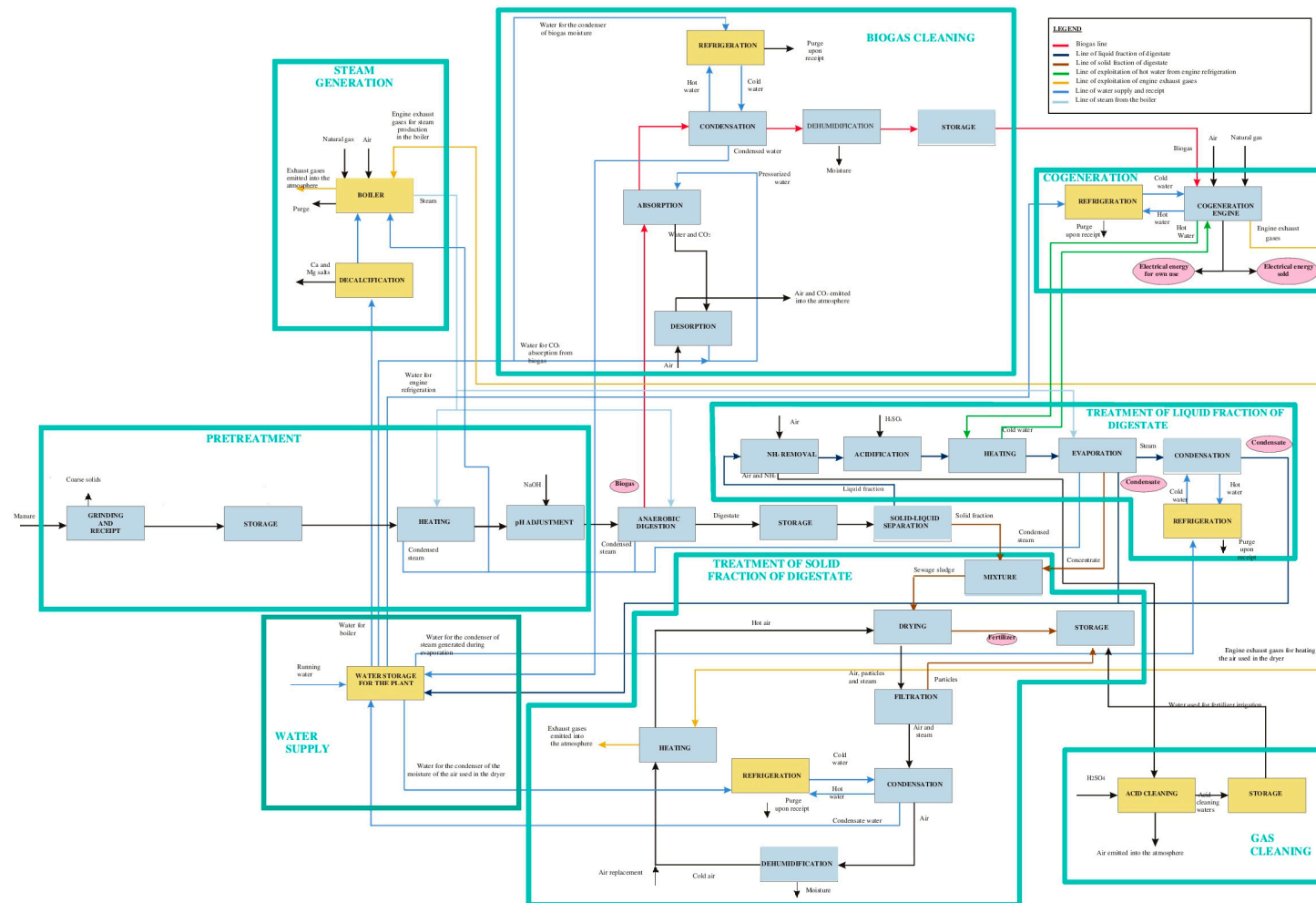
Figure 1. Flowchart of the pig manure treatment plant.

2.1.1. Pretreatment

Pig manure unloading into the reception pit is carried out through a metal sieve, which is used to separate coarse solids from wastewater. Those solids are then removed by an authorized manager.

Afterwards, the supply flow must be conditioned before entering the anaerobic digester. This conditioning consists on reaching a temperature within the mesophilic range (35 °C), by means of a heating process, and a pH value between 6.5 and 7.5, by means of the addition of sodium hydroxide.

Table 2 shows the operation conditions of the different pretreatment stages.

Table 2. Operation conditions during pretreatment stage.

Process	Equipment	Operating Conditions
Filtering	Sieve	Opening mesh = 10 mm
Reception	Pit	$V = 80$ m^3
Storage	Tank	$V_1 = V_2 = 450$ m^3
Heating	Heat exchanger	$m_{steam} = 560$ kg h^{-1}; $A = 4$ m^2
pH adjustment	Tank	$V = 1$ m^3

2.1.2. Anaerobic Digestion

Table 3 shows the operation conditions for the three anaerobic digesters, whose heating system consisting on a perimeter pipe is also characterized by means of the heating steam flow and the necessary heat exchange surface.

Table 3. Operation conditions during the stage of anaerobic digestion.

Process	Equipment	Operating Conditions
Anaerobic digestion	Anaerobic digester	$V_1 = V_2 = V_3 = 4100$ m^3; HRT = 28 days; T = 35 °C; $m_{steam} = 680$ kg h^{-1}; $A = 11$ m^2

2.1.3. Biogas Cleaning and Conditioning

Table 4 shows the different cleaning and conditioning processes of the biogas, which is used as fuel for the motor-generator in order to obtain electrical energy.

Table 4. Operation conditions during the stage of biogas cleaning and conditioning.

Process	Equipment	Operating Conditions
Absorption	Packed column	$m_{water} = 28$ kg h^{-1}; d = 0.90 m; H = 2.25 m
Desorption	Packed column	$m_{air} = 18$ kg h^{-1}; d = 1.50 m; H = 3.50 m
Condensation	Heat exchanger	$m_{water} = 1$ m^3 h^{-1}; $A = 0.3$ m^2
Storage	Gasometer	$V = 2100$ m^3; $t_{retention} = 27$ h; P = 2.50 atm

2.1.4. Digestate Treatment

Table 5 shows the different treatment processes for the liquid and the solid fractions of digestate, aimed at obtaining water and biofertilizer, respectively.

Table 5. Operation conditions during the stage of digestate treatment.

Process	Equipment	Operating Conditions
Storage	Tank	$V = 225 \ m^3$
Solid-liquid separation	Centrifugal decanter	$m_{solid,fraction} = 2000 \ kg \ h^{-1}$; $m_{liquid,fraction} = 13,600 \ kg \ h^{-1}$
Liquid Fraction		
NH_3 removal	Absorption column	$m_{air} = 10,200 \ kg \ h^{-1}$; d = 1.50 m; H = 3.75 m
Acidification	Tank	$V = 25 \ m^3$
Heating	Heat exchanger	$m_{water} = 216,000 \ kg \ h^{-1}$; $A = 21 \ m^2$
Evaporation	Evaporator	$A_1 = A_2 = 45 \ m^2$
Condensation	Heat exchanger	$m_{water} = 400,000 \ kg \ h^{-1}$; $A = 490 \ m^2$
Solid Fraction		
Mixture	Mixer	$V = 28 \ m^3$; $m_{outlet} = 2500 \ kg \ h^{-1}$
Drying	Dryer	$m_{air} = 62,000 \ kg \ h^{-1}$; d = 2.5 m; H = 3 m
Filtration	Bag filter	$A = 250 \ m^2$
Storage	Storage location	L = 20 m; A = 10 m; H = 5 m
Condensation	Heat exchanger	$m_{water} = 140 \ m^3 \ h^{-1}$; $A = 65 \ m^2$

2.2. Indicators of Circular Economy

Several indicators of circular economy that allow to determine the efficiency of the use of resources, the minimization of waste generation and the conversion of pig manure into a technological nutrient are defined hereafter [5,6]. These indicators are considered within the circular economy model applied to the process of pig manure treatment.

Such indicators will be defined in relation to the three resources that are recovered from pig manure during the process: water, biofertilizer, and biogas (Figure 1).

2.2.1. Indicators of Circular Economy for Water

The indicator of circular economy efficiency for water ($I_{w,ce}$) provides information about the reduction in the water used for pig manure treatment.

Such indicator is defined according to Equation (1):

$$I_{w,ce} = \frac{\sum_{i=1}^{n} Q_{w,i}}{Q_{w,t}} \cdot 100 \tag{1}$$

where $Q_{w,i}$ is the volumetric flow rate of water recovered during stage i in the process of pig manure treatment, and $Q_{w,t}$ is the total volumetric flow rate of water used during the process of pig manure treatment.

This indicator can range between 0% and 100%. 0 means that no water was recovered during the process and 100% is the ideal case of sustainability, where there is such recovery of water during the process that no external consumption occurs.

In addition, an indicator of technological nutrient performance for water ($I_{w,tn}$) is defined according to Equation (2):

$$I_{w,tn} = \frac{\sum_{i=1}^{n} Q_{w,i}}{Q_{sw}} \tag{2}$$

where Q_{sw} is the volumetric flow rate of pig manure treated during the process.

This indicator provides information about the water volume that can be obtained and reintroduced into the process according to the pig manure volume (technological nutrient) that is treated in the plant.

2.2.2. Indicators of Circular Economy for Biofertilizer

The indicator of circular economy efficiency for the biofertilizer ($I_{bf,ce}$) provides information about the production of biofertilizer during the process of pig manure treatment.

Such an indicator is defined according to Equation (3):

$$I_{bf,ce} = \frac{\sum_{i=1}^{n} m_{bf,i}}{m_{digestate}} \cdot 100 \tag{3}$$

where $m_{bf,i}$ is the mass flow rate of biofertilizer obtained during stage i of the process of pig manure treatment, and $m_{digestate}$ is the mass flow rate of digestate generated during the anaerobic digestion stage.

This indicator can range between 0 and values below 100%, indicating the production rate of the biofertilizer during the process.

The indicator of technological nutrient performance for the biofertilizer ($I_{bf,tn}$) can be defined as shown in Equation (4):

$$I_{bf,tn} = \frac{\sum_{i=1}^{n} m_{bf,i}}{Q_{sw}} \tag{4}$$

This indicator provides information about the amount of biofertilizer generated during the treatment process with respect to the volume of pig manure that will be treated in the plant.

2.2.3. Indicators of Circular Economy for Biogas

The indicator of circular economy efficiency for biogas ($I_{bg,ce}$) provides information about the reduction in natural gas consumption in order to carry out pig manure treatment.

Such an indicator is defined according to Equation (5):

$$I_{bg,ce} = \frac{Q_{bg,treated}}{Q_{ng,t}} \cdot 100 \tag{5}$$

where $Q_{bg,treated}$ is the volumetric flow rate of biogas recovered during the process of pig manure treatment and $Q_{ng,t}$ is the volumetric flow rate of natural gas used during the process of pig manure treatment.

This indicator can range between 0% and 100%. 0 means that no biogas was recovered during the process and 100% is the ideal case of sustainability, where the biogas flow rate recovered is the same as the one used in the treatment plant.

The indicator of technological nutrient performance for the biogas ($I_{bg,tn}$) can be defined as shown in Equation (6):

$$I_{bg,tn} = \frac{Q_{bg,treated}}{Q_{sw}} \tag{6}$$

This parameter indicates the volume of biogas generated during the anaerobic digestion treatment depending on the volume of pig manure treated in the plant.

The reduction in CO_2 emissions ($ER_{CO2,ce}$) as a consequence of the use of biogas during the process can be calculated from $Q_{ng,t}$, the factor of CO_2 emissions of natural gas ($EF_{CO2,ng}$) and $I_{bg,ce}$, as shown in Equation (7):

$$ER_{CO2,ce} = Q_{ng,t} \cdot EF_{CO2,ng} \cdot I_{bg,ce} \tag{7}$$

3. Results and Discussion

3.1. Water Production

The water needs of the plant come from the stages of biogas absorption, the steam generation boiler, and the cooling towers of the condenser of the steam contained in the biogas, cogeneration engine, condenser of the steam generated during evaporation, and condenser of the steam contained in the air used during the drying process. On the contrary, that water generated during the process comes from three subprocesses, such as evaporation, condensation of the steam contained in the air used

during the drying process, and condensation of the steam contained in the biogas obtained during anaerobic digestion. Table 6 shows the values of water consumption and generation.

Table 6. Processes of the treatment plant where water is used and generated.

Process	Water Flow ($m^3\ h^{-1}$)
Consumption	
Biogas absorption	0.35
Cooling tower of the condenser of the steam contained in the biogas	0.02
Cooling tower of the cogeneration engine	4.02
Cooling tower of the condenser of the steam generated during evaporation	20.00
Cooling tower of the condenser of the steam contained in the air used during the drying process	6.70
Steam generation boiler	0.01
$Q_{w,t}$	**31.10**
Generation	
Evaporation (1)	12.80
Condensation of the steam contained in the air used during the drying process (2)	1.80
Condensation of the steam contained in the biogas obtained during anaerobic digestion (3)	0.02
$\sum_{i=1}^{3} Q_{w,i}$	**14.62**

The higher water generation is due to the evaporation process of the treatment of liquid fraction of digestate, with a value of 12.80 $m^3\ h^{-1}$ (Table 6).

3.2. Biofertilizer Production

The value of the digestate mass flow rate obtained during the stage of anaerobic digestion is $m_{digestate}$ = 15,600 kg h^{-1}. Biofertilizer will be obtained from it. Table 7 shows the stages of the process where it is generated.

Table 7. Processes of the treatment plant during which biofertilizer is produced.

Process	Biofertilizer Flow (kg h^{-1})
Drying (1)	561.00
Filtration (2)	60.00
Gas cleaning (3)	120.00
$\sum_{i=1}^{3} m_{bf,i}$	**741.00**

As shown in Table 7, the highest production of fertilizer is carried out during the drying stage of that sewage sludge resulting from the mixture of the solid fraction of digestate and the concentrate of the evaporation process corresponding to the treatment of liquid fraction of digestate (Figure 1). The fertilizer obtained during the filtration stage corresponds to the particles that may be contained in the air used during the drying process, this is why its value is lower. Regarding the gas cleaning stage, liquid fertilizer enriched with ammonium sulfate is obtained, with which the solid biofertilizer from the two previous stages is irrigated.

3.3. Biogas Production

Natural gas consumption in the pig manure treatment plant comes from the stage of steam generation in the boiler as well as the cogeneration stage. Biogas production is carried out during the anaerobic digestion stage. This biogas undergoes a purification process so that it can be used in the cogeneration process (Figure 1). Table 8 shows the natural gas consumption and biogas production values.

Table 8. Processes of the treatment plant during which water is used and generated.

Process	Gas Flow ($m^3 h^{-1}$)
Consumption	
Steam generation boiler	473.75
Cogeneration engine	1027.00
$Q_{ng,t}$	**1500.75**
Generation	
Anaerobic digestion	80.00
$Q_{bg,treated}$	**80.00**

3.4. Indicators of Circular Economy

Table 9 shows the values of the six indicators of circular economy evaluated for the process of pig manure treatment.

Table 9. Indicators of circular economy efficiency and technological nutrient performance for water, biofertilizer and biogas produced during the process of pig manure treatment. $I_{w,ce}$ (indicator of circular economy efficiency for water), $I_{w,tn}$ (indicator of technological nutrient performance for water), $I_{bf,ce}$ (indicator of circular economy efficiency for biofertilizer), $I_{bf,tn}$ (indicator of technological nutrient performance for biofertilizer), $I_{bg,ce}$ (indicator of circular economy efficiency for biogas), $I_{bg,tn}$ (indicator of technological nutrient performance for biogas), $ER_{CO2,ce}$ (reduction in CO_2 emissions as a consequence of the application of circular economy).

Indicator of Circular Economy	Value
Water	
$I_{w,ce}$ (%)	47.01
$I_{w,tn}$ (m^3 water m^{-3} pig manure)	0.97
Biofertilizer	
$I_{bf,ce}$ (%)	4.75
$I_{bf,tn}$ (kg biofertilizer m^{-3} pig manure)	49.40
Biogas	
$I_{bg,ce}$ (%)	5.33
$I_{bg,tn}$ (m^3 biogas m^{-3} pig manure)	5.33
$ER_{CO2,ce}$ (kg CO_2 h^{-1}) [1]	171.98

Note: [1] $EF_{CO2,ng}$ = 2.15 kg CO_2 m^{-3} natural gas [43].

As shown in Table 9, the treatment process allows water, biofertilizer, and biogas recovery from pig manure, turned into a technological nutrient. The water obtained allows for the reduction of water consumption for such process by 47.01%, the biogas obtained allows to the reduction of natural gas consumption by 5.33%, and, on top of that, 4.75% biofertilizer is produced from the digestate obtained during the anaerobic digestion stage.

Furthermore, those indicators of technological nutrient production indicate that per 1 m^3 pig manure h^{-1} treated, it is possible to obtain 0.97 m^3 water h^{-1}, 49.40 kg biofertilizer h^{-1}, and 5.33 m^3 biogas h^{-1}. Obtaining such a quantity of biogas leads to a reduction in emissions of 171.98 kg CO_2 h^{-1}.

In light of this, Table 10 shows the biogas production potential reported in several works all over the world.

Table 10. Summary of literature findings comparing the biogas production potential during anaerobic digestion of pig manure.

Zone	Biogas Production Potential	References
South Africa	18.72 m^3 biogas m^{-3} pig manure	[44]
China	6.38 m^3 biogas m^{-3} pig manure	[45]
China	1.43–2.15 m^3 biogas m^{-3} pig manure	[46]
Australia	0.480 m^3 biogas kg^{-1} VS	[47]
Spain	0.170 m^3 biogas kg^{-1} VS	[48]
South Korea	0.242 m^3 biogas kg^{-1} VS	[49]
South Korea	0.394 m^3 biogas kg^{-1} VS	[50]
Colombia	0.437 m^3 biogas kg^{-1} VS	[51]

In the present research, $I_{bg,tn}$ shows a value of 5.33 m^3 biogas m^{-3} pig manure (or 0.888 m^3 biogas kg^{-1} VS) that is within the range found in literature. It should be highlighted that the biogas production potential is higher than the different works included in Table 10, with the exception of the studies that were carried out in South Africa (18.72 m^3 biogas m^{-3} pig manure) and China (6.38 m^3 biogas m^{-3} pig manure).

The values obtained for the indicators of circular economy efficiency and technological nutrient performance bring to light the importance of the application of the circular economy model in pig manure treatment. In this regard, the proposal of these indicators has been considered due to its significant weight in the process of pig manure treatment. In this way, those responsible for making decisions in these treatment processes can have access to these indicators and make operational decisions in that sector in order to make it generate as few negative externalities as possible and be under way to a circular economy production model. Thus, the introduction of the indicators of circular economy in the present work could facilitate the development of new strategies for pig manure treatment concerning the reduction in waste generation and the consumption of renewable energy, according to the requirements of the European Union.

4. Conclusions

The present article provides the first indicators for circular economy efficiency, as well as tools for technological nutrient performance for the pig farming industry, allowing the quantification of the degree of approximation to a circular economy model.

This study explains that pig manure can be considered as a technological nutrient that can also be reintroduced into the production system, enabling the recovery of those resources present during such processes, such as water, nutrients, and energy, from a treatment process whose central nucleus is anaerobic digestion. Such resources are used in the process itself, as in the case of water, reducing water consumption by 47.01%, biogas, reducing gas natural consumption by 5.33%, and some other products resulting directly from this type of industrial activity, as in the case of the biofertilizer. In addition, the treatment process allows the recovery of 0.97 m^3 water m^{-3} pig manure, 49.40 kg biofertilizer m^{-3} pig manure, and 5.33 m^3 biogas m^{-3} pig manure. In this way, the proposed indicators can be taken into account by the production plant managers in order to improve the efficiency of the use of resources and the minimization of waste generation.

Consequently, this research provides the pig farming industry with new ideas and measuring tools so that it becomes a reference in sustainable production and contributes to reduce the negative polluting effects, in environmental terms, of pig manure generation. This article provides relevant details so that pig industry can develop strategies for pig manure treatment in compliance with the new requirements of the European Union in relation to waste generation in 2020 and renewable energy consumption in 2030 (27%), and, in this way, being able to comply with this regulation, which highlights the importance of the circular economy. In addition, it is also a way of incorporating innovations in its

processes to make it more sustainable from the environmental point of view, contributing to a higher effectiveness in terms of a decrease of negative externalities.

Author Contributions: All authors participated equally in the conception and design of this research, and the elaboration of this paper. All authors read and approved the final manuscript.

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

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