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Consequential Life Cycle Assessment of Swine Manure Management within a Thermal Gasification Scenario

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Abstract: Sustainable swine manure management is critical to reducing adverse environmental impacts on surrounding ecosystems, particularly in regions of intensive production. Conventional swine manure management practices contribute to agricultural greenhouse gas (GHG) emissions and aquatic eutrophication. There is a lack of full-scale research of the thermochemical conversion of solid-separated swine manure. This study utilizes a consequential life cycle assessment (CLCA) to investigate the environmental impacts of the thermal gasification of swine manure solids as a manure management strategy. CLCA is a modeling tool for a comprehensive estimation of the environmental impacts attributable to a production system. The present study evaluates merely the gasification scenario as it includes manure drying, syngas production, and biochar field application. The assessment revealed that liquid storage of manure had the highest contribution of 57.5% to GHG emissions for the entire proposed manure management scenario. Solid-liquid separation decreased GHG emissions from the manure liquid fraction. Swine manure solids separation, drying, and gasification resulted in a net energy expenditure of 12.3 MJ for each functional unit (treatment of 1 metric ton of manure slurry). Land application of manure slurry mixed with biochar residue could potentially be credited with 5.9 kg CO_2-eq in avoided GHG emissions, and 135 MJ of avoided fossil fuel energy. Manure drying had the highest share of fossil fuel energy use. Increasing thermochemical conversion efficiency was shown to decrease overall energy use significantly. Improvements in drying technology efficiency, or the use of solar or waste-heat streams as energy sources, can significantly improve the potential environmental impacts of manure solids gasification.

Keywords: life cycle assessment; environmental impact; greenhouse gas; gasification; swine manure management

1. Introduction

Agricultural systems are significant contributors to global climate change and ecosystems degradation [1]. Local, regional, and global agreements are increasingly mandating legislative and regulatory actions to restrict emissions to mitigate the short-term and long-term environmental degradation. However, both legislative and regulatory efforts to reduce environmental impacts, especially greenhouse gas (GHG) emissions, will eventually put a more significant burden on agricultural and industrial sectors as well as increase the cost of production. Livestock production, in particular, has been recognized as a significant source of GHG emissions and a driver of both freshwater and marine water eutrophication [2,3]. Therefore, the vulnerability of livestock production and the agriculture sector to climate change further incentivizes the search for and adoption of sustainable agricultural practices [4].

In livestock production, manure management is a significant source of direct GHG emissions, such as methane (CH_4) and nitrous oxide (N_2O) [5]. Land application is the most common practice to handle swine manure to use available nutrients for crop production. However, applying swine manure to crop and grass fields where nutrients are available more than agronomic crop needs or where fields have historically received large volumes of manure application increase environmental risks to surrounding ecosystems. Liquid manure management systems, relevant to swine production, are also a significant source of gaseous emissions. Liquid manure storage promotes anaerobic conditions, which transform organic matter into CH_4 and ammonia (NH_3). Besides, uncontrolled anaerobic and aerobic conditions initiate nitrification-denitrification processes, which convert a share of manure nitrogen to N_2O, which is a potent GHG. Solid-liquid separation of swine manure has been recognized as an emission mitigation strategy. However, increased N_2O and CH_4 emissions have been reported during storage of manure-separated solids [6]. Transforming separated solids into a gas fuel (syngas) and a stable nutrient-rich co-product (biochar), via gasification, can potentially reduce emissions associated with manure-separated solids and generate value-added products. Furthermore, gasification-derived biochars have been shown to have adsorbing characteristics for various organic contaminants such as *p*-Cresol [7,8].

Evaluating emissions and impacts associated with this conversion strategy, i.e., gasification of swine manure solids, can facilitate adoption and expand the set of technologies available to livestock producers for manure management. Life cycle assessment (LCA) is an essential tool to assist decision-makers by evaluating the environmental performance of proposed management strategies. According to ISO standard 14040 [9], LCA considers the various input and output flow, and the corresponding environmental burdens, resulting from production, consumption, and disposal of associated product systems. Energy recovery from swine manure incineration was found to be a promising pathway to reduce GHG emissions associated with manure management [10]. Several LCA studies have reported on the performance on anaerobic digestion as manure management and energy recovery as a sole feedstock or in combination with other biomass streams [11–13]. Wu et al. [10] performed an LCA comparing GHG emissions between land application and gasification as manure management practices. The study showed that gasification has high potential to reduce GHG emissions due to the environmental benefits of syngas production and biochar application to crop field. Biochar also has been used for carbon sequestration, soil amendment and biomass waste management [14].

In a comprehensive review of swine manure conversion technologies, Sharara and Sadaka [15] highlighted the scarcity of research studies that investigated swine manure solids gasification and pyrolysis. Accordingly, it was recommended to develop an LCA of swine manure management systems. Therefore, the objective of this study is to evaluate potential environmental impacts of a manure management scenario that utilizes thermal gasification of swine manure solids as a disposal/energy retrieval strategy using consequential life cycle assessment (CLCA) methodology.

2. Methods

2.1. LCA Goal and Scope

The goal of this CLCA is to determine the impacts associated with swine manure management using gasification for manure solids. Figure 1 shows a schematic diagram of the proposed swine manure management (SMM) scenario. The scope of this CLCA covers manure management activities associated with 1000 kg of flushed swine manure at 5% dry matter content, without accounting for animal maintenance (feed, drinking water, climate control - all assumed to be unaffected by treatment), until the land application of both the liquid fraction (slurry) and the solid fraction (biochar). The functional unit (FU) is the treatment of one metric ton (1000 kg) of swine manure slurry, at 5% DM, via gasification and land application. The thermal gasification of manure solids produces three co-products: syngas, heat, and biochar. All three co-products were modeled as displacing existing processes in the system with surpluses used to displace their alternatives beyond the system boundary. A share of the produced syngas is consumed as fuel in a boiler, while the excess syngas is considered a replacement for natural gas. The heat generated during the thermal gasification is used for drying, and biochar is land applied as a fertilizer replacement.

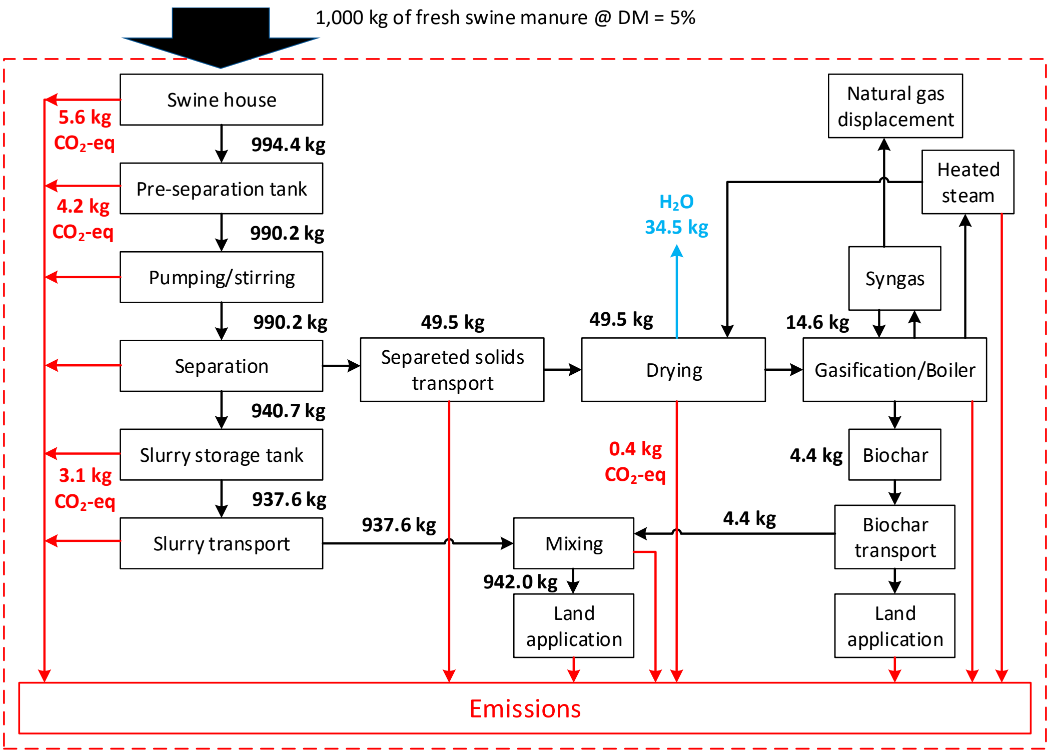

Figure 1. The scope of proposed swine manure management scenario illustrating mass balances and emissions flows (Note: black arrows represent main product flow; red arrows represent direct and indirect greenhouse gas (GHG) emissions. Blue arrow represents water evaporation. Numbers in red are direct emissions of GHG in kg CO_2-eq).

The excreted manure (urine and feces) is flushed from shallow pits under the house. The flushed manure is stored in a holding pond, and stirred, before being pumped into the separation stage. Manure separation is accomplished using a screw press separator. This class of size-separators utilizes a tapered screw and a fine-mesh screen (0.75–3 mm) to fractionate the manure into solids-rich and liquids-rich fractions. The solids-rich fraction is transported to a thermochemical conversion facility that contains a dryer, a gasifier, and a gas boiler. The manure gasification is accomplished in an atmospheric, fluidized-bed gasifier to produce syngas, which is subsequently fired (burned) in the gas boiler for heat, in addition to biochar. The liquid-fraction (slurry) is stored, then transported to an agricultural field for land application. In this model, the emissions associated with land application of biochar and slurry are presented in detail separately first, then combined to estimate the total impacts of biochar-slurry land application. The total impacts represent the summation of the impacts from each substrate without including any synergistic effects. SimaPro© 8.5.2 software (PRé Consultants, The Netherlands) and ecoinvent v3.4 database [16] with IMPACT World+ midpoint method [17] were used to model the impacts. We modified the characterization factors in IMPACT World+ by adopting the most recent Intergovernmental Panel on Climate Change (IPCC, v1.02) 100-year global warming potentials (GWP 100a): CH_4 biogenic: 27.8 kg CO_2-eq, CH_4 fossil: 30.5 kg CO_2-eq and N_2O: 265 kg CO_2-eq [18]. The inventory of mass, energy, and emission flows, in each stage, is presented in the following sections.

2.2. Life-Cycle Inventory Assessment

2.2.1. Swine House

According to manure characteristics standard [19], the amount of total solids in as-excreted swine manure is between 5% and 10% by weight for grow-finish pigs. Manure can be collected from barns through flushing, scrapping, or using pull-plug systems that rely on gravity. Collection systems significantly impact the concentration of solids in the collected manure. In this study, the composition of swine manure solids was taken from first-hand analyses of manure solids sampled from the gravity-collected slurry in a feeder-finisher farm in Washington County, Arkansas. Table 1 shows the characteristics of swine manure solids. The accumulated manure is collected every two weeks by gravity using a pull-plug system (no energy or mechanical power is needed for drainage). During the 2-week storage, various biogenic emissions, namely NH_3, N_2O, CO_2, and CH_4, are released due to aerobic and anaerobic activities in the manure substrate. NH_3 and N_2O emissions as nitrogen during this period were estimated at 16% and 0.5% of total manure nitrogen [20]. Manure-related GHG emissions, i.e., CH_4 and N_2O were estimated using the IPCC Tier 1 approach for GHG emissions in livestock [1].

Table 1. Characteristics of swine manure under the current study.

Characteristics	Value	Units	Characteristics	Value	Units
Dry matter (DM)	5.0	%	P (Ash)	20.9	%
Volatile matter (DM)	81.6	%	K (Ash)	21.1	%
Ash (DM)	18.4	%	Na (Ash)	10.3	%
C (DM)	50.8	%	Ca (Ash)	20.5	%
Total-N (DM)	4.3	%	Mg (Ash)	12.1	%
O (DM)	21.0	%	Cu (Ash)	0.01	%
H (DM)	6.9	%	Zn (Ash)	0.04	%
S (DM)	1.3	%			

2.2.2. Pre-Separation Tank/Stirring and Mixing

Pre-separation storage was modeled as an opened storage tank. The projected NH_3 loss is 2% of the total N in the manure [21]. IPCC guidelines for GHG emissions were used to estimate the N_2O and CH_4 emissions in the pre-separation tank. For the agitation/mixing step, Wesnaes et al. [21] and Nguyen et al. [22] reported that the energy requirements for pumping and stirring 1000 kg of manure slurry to be 0.5 kWh and 1.2 kWh, respectively. Thus, the total energy consumption associated with this stage (stirring and pumping) was taken as 1.7 kWh.

2.2.3. Mechanical Separation and Separated Solids Transport

Moller et al. [23] estimated the power required for manure solid-liquid separation using a mechanical screen press to be 0.50 kWh per metric ton. Therefore, the energy required for separation was modeled as 0.5 kWh. The U.S. electricity mix was used to model the impacts of electric power utilization. No air emissions or water contamination are associated with manure during this stage.

The separation indices reported for screw presses [24] were used to determine the amount and composition of separation products. In that study, the solids content in the original slurry varied from 1.8% to 6.3%. As shown in Table 2, the separation index (%) is defined as the mass of a given compound in the solid fraction to the mass of that compound in the original (unseparated) slurry. The mass of the separated solids fraction (containing both solids and slurry) ranges between 5.0% and 7.3% [25,26]; the lower value (5.0%) was used in this study. The separated solid fraction (TS = 28% *weight basis*) were assumed to be transported 500 meters (0.5 km) from the separation platform to the drying and conversion facility. Emissions associated with this step were estimated per shipping unit, i.e., ton-kilometer (tkm) using ecoinvent (v3.4) inventory (transport, tractor, and trailer, agricultural {GLO}| market for | Conseq, U) for farm operations [16].

Table 2. Separation indices for mechanical screw press separation [23].

	Raw Pig Slurry	Separation Index (%)			
	DM (%)	Volume	Dry Matter	N-Total	P-Total
Mean [1]	4.7	5.75	35	11	20.3
Standard Deviation	(2.01)	(1.50)	(16)	(10)	(16.5)

[1] Based on data collected from ref. [23].

2.2.4. Drying

Gasifying organic material requires that the moisture content should be 15% or lower [24,27]. Therefore, the separated solids fraction must be dried first. Drying can be accomplished passively by relying on solar heating and natural air circulation, or through the mechanical circulation of heated air through the wet mixture using blowers or fans. Ideally, for such a system to be efficient, the material is moved inside the dryer to ensure quick and uniform dryness. Passive drying of swine manure solids can be a source of objectionable odors and can reduce the organic carbon content of the material. Therefore, a heated air-drying technique was modeled for this study. The thermal energy required to remove 1 kg of moisture from manure was reported to be 2.3 MJ [23]. Hospido *et al.* [28] evaluated different scenarios for utilizing solid sludge from urban wastewater treatment plants (WWTP) using 1,000 kg of dried sludge as the unit basis. In their study, the electricity and heat consumption associated with sludge drying were 118 kWh and 1,638 kWh per 1 metric ton of dried sludge, respectively.

During drying, as much as 20% of the manure-N was reported to volatilize, typically as NH_3 [29]. Also, C loss during drying was reported to be around 4%. In the municipal sludge drying process model, 44.3 g of volatile organic compound (VOC) emissions were reported per ton of dried sludge. The same emissions factor was used to model the manure emissions in this study.

2.2.5. Gasification/Boiler

In this thermochemical conversion process, the dry manure solids are transformed at temperatures between 600 and 800 °C to gas (referred to as producer gas, or syngas) in addition to biochar, and a small amount of condensable material (tar) is produced. Gasification utilizes air, or another oxidizing agent, to partially oxidize the biomass C into CO and CO_2. However, given the scarcity of the data on the gasification of swine manure solids, the dataset used in this study (Table 3) was compiled from available studies on swine manure solids and feedstock, such as, poultry litter, sewage sludge, cattle feedlot manure, that have similar characteristics as swine manure solids, i.e., high ash, and nitrogen content. The primary product, syngas, is combusted in a steam boiler to generate steam that is used to satisfy heating needs on the farm, e.g., the drying manure solids, and heating the farrowing crates. The syngas displaces natural gas demand and, consequently, the impacts associated with natural gas production. To account for the summer season when the heating is not necessary on the farm, we deducted 25% of the heat production to be claimed as a credit in the computational modeling.

Table 3. A gasification process model for 1 kg of dry (15% moisture) swine manure solids.

Parameters	Values	Source
Air requirements (kg_{air} kg^{-1})	2.54	Calculated from composition, ER = 0.20
Manure solids HHV † (MJ kg^{-1})	19–20	[30,31]
Cold-gas efficiency (%)	50–80	[32]
Boiler thermal efficiency (%)	78	[33]
Char yield (g kg^{-1})	300–490	[32,33]
Electricity req. (kWh kg^{-1})	0.339	[34]
Thermal energy req. (MJ kg^{-1})	1.2	[35]

† HHV: higher heating value.

The cold-gas efficiency in Table 3 is the chemical energy retained in the syngas as a share of the total chemical energy in the feedstock, without considering the gas sensible heat. In this case, however, since the syngas is used to replace a heat source (natural gas), both the sensible and chemical energies in the syngas were considered. Accordingly, the conversion efficiency increases, with thermal gas efficiency (HGE) taken to be between 60% and 90%. A 70% HGE was used in this model. Accordingly, the amount of heat generated (MJ) due to gasification was calculated after subtracting the thermal energy required for the process (calculated using the pyrolysis enthalpy in Table 3 taken here to be 1.0 MJ kg^{-1}). Gasification also yields a biochar fraction, which is utilized as a soil amendment. The biochar produced was assumed to be a nitrogen-free co-product since all nitrogen typically devolatilizer during gasification as N-species. P and K were assumed to be sequestered entirely in the biochar fraction. Table 4 presents the emission associated with the current study via the gasification facility for the swine manure solids.

Table 4. Emissions to the air resulting from the gasification process (per 1 kg of dry matter of swine manure solids).

Substance	Value (g)	Substance	Value (g)
CO_2	1458.5	VOCs	0.016
NOx	1.1400	HF	0.0005
CO	0.1460	Hg	0.0001
SO_2	0.076	As	0.0001
HCl	0.047	Ni	0.0000
PM	0.018	Cd	0.0000

2.2.6. Biochar Transport and Land Application

The environmental emissions associated with biochar transport to the field were considered with a transportation distance assumed to be 10 km (6.2 miles), which is slightly more than the upper bound on average manure hauling distances, i.e., between 1.6 and 6.4 km (1 and 4 miles). Biochar land application is beneficial both as a fertilizer/soil conditioner and as a carbon sequestration option [36]. In this study, the benefits of biochar application to the soil were determined as the avoided synthetic fertilizers due to the presence of P and K in the biochar. Nutrient credits were assigned for P and K in biochar as 80% equivalency of commercial fertilizer, according to the Wisconsin study [37]. Additional benefits of biochar application include improved water holding capacity and reduced N_2O emissions. However, due to the scarcity of quantifiable data on these benefits and the strong dependence on the crop, soil and climate conditions, these additional benefits are not considered in this study, i.e., no GHG emissions from the biochar field application were considered. The amount of avoided P_2O_5 and K_2O fertilizers, and sequestered CO_2 were determined, to be 0.71 kg P_2O_5, 0.66 kg K_2O, and 3.43 kg CO_2 per ton of functional unit.

2.2.7. Post-Separation Tank (Liquid-Fraction)

The separated slurry is stored in an exposed tank until it is transported to a field for application. During storage, the organic fraction of this slurry transforms, resulting in GHG emissions. The following section describes the computations for the various emissions. IPCC guidelines [38] were used to estimate CH_4 emissions in the swine house, and the estimating method used for the pre-separation tank was also used here to estimate emissions during post-separation storage of the liquid slurry. It should be noted that the volatile solids loading (VS) in this storage step is much lower than in the pre-separation tank, i.e., 21.5 kg per functional unit. Similarly, NH_3 and N_2O emissions were estimated using emission factors outlined for pre-separation tank emissions.

2.2.8. Liquid Fraction Transport, Mixing with Biochar, and Land Application

The liquid fraction transportation distance to the application field was assumed to be equal to that for biochar, 10 km. This distance has been used before in a similar study to model the impacts of dairy cow slurry digestion and land application [39]. The energy requirement for slurry and biochar mixing is 1.2 kWh ton^{-1}, and the land application energy requirements and emissions were modeled using the vacuum spreader model available in the ecoinvent v3.4 database (Ecoinvent Centre, 2019). The impacts of slurry application (without the biochar) are presented in the following section. Table 5 below presents the summary of inputs and emissions for the functional unit as well as nutrient credits associated with land application of liquid slurry and biochar. The avoided N fertilizer value was calculated from N availability in a liquid slurry, using Delin et al. [39], as 52% equivalency of commercial nitrogen fertilizer.

Table 5. Summary of emissions, energy, and transportation requirements as well as an avoided burden for the functional unit.

1. Swine house			
NH_3 emissions (kg)	0.418	CO_2 emissions, biogenic (kg)	2.82
N_2O emissions (kg)	0.017	CH_4 emissions (kg)	2.36
2. Pre-separation storage tank			
NH_3 emissions (kg)	0.052	CO_2 emissions, biogenic (kg)	2.14
N_2O emissions (kg)	0.017	CH_4 emissions (kg)	1.94
3. Stirring and pumping			
Electrical power requirements (kWh)	1.7		
4. Mechanical separation			
Electrical power requirement (kWh)	0.5		
5. Solids transportation			
Transportation (tkm)	0.025		
6. Drying (solid fraction)			
Heat requirements (MJ)	86.1	VOC emissions (kg)	0.00064
Electricity requirements (kWh)	1.72	NH_3 emissions (kg)	0.43
Water requirement (m^3)	0.222		

Table 5. *Cont.*

7. Gasification-Boiler (solid fraction)			
Electricity requirements (kWh)	4.94	HCl emissions (g)	0.47
Air needed (kg)	37.05	PM emissions (g)	0.18
Thermal energy requirement (MJ)	17.5		
Generated heat (MJ)	140.7	VOCs emissions (g)	0.16
Char Produced (kg)	4.38	HF emissions (g)	0.005
CO_2 emissions (kg)	1.458	Hg emissions (g)	0.001
NO_x emissions (g)	11.38	As emissions (g)	0.0009
CO emissions (g)	1.46	Ni emissions (g)	0.0006
SO_2 emissions (g)	0.76	Cd emissions (g)	0.0001
8. biochar transportation (solid fraction)			
Transportation (tkm)	0.044		
9. Post-land application for the biochar (solid fraction)			
Avoided P_2O_5 (kg)	0.71	P leaching (kg)	0.039
Avoided K_2O (kg)	0.66		
10. Post-separation storage tank (liquid fraction)			
NH_3 emissions (kg)	0.033	CO_2 emissions, biogenic (kg)	1.78
N_2O emissions (kg)	0.011	CH_4 emissions (kg)	1.24
11. Slurry transportation (liquid fraction)			
Transportation (tkm)	9.395		
12. Mixing and land application (solid and liquid fractions)			
Mixing (kWh)	1.2		
13. Post-land application for the slurry (liquid fraction)			
NH_3 emissions (kg)	0.204	Avoided P_2O_5 (kg)	2.62
N_2O emissions (kg)	0.021	Avoided K_2O (kg)	1.13
CO_2 emissions, biogenic (kg)	27.2	NO_3 leaching (kg)	1.8
Avoided N fertilizer (kg)	0.398	P leaching (kg)	0.15

NH_3 devolatilization resulting from manure land application is among the primary sources of N emissions in the agricultural sector. Rates of NH_3 emissions vary significantly with variability in manure slurry characteristics, soil type, and weather conditions. Misselbrook et al. [40] studied the influence of manure type (cattle, and pig manure), and land type (arable and grassland) on NH_3 emissions. They reported NH_3 emissions between 6.0 and 21.5% of the total ammoniacal nitrogen (TAN) in the pig manure. Sommer and Hutchings [41] reported NH_3 emissions to be 5% of total NH_4 in an applied slurry with trail hose application, and 8-10% of total NH_4 under broad spreading. According to literature, an estimated 39% of TAN in swine slurry devolatilizes as NH_3 during spring season land application [42]. In this study, NH_3 devolatilization was modeled as 20% of TAN in the slurry. The TAN was taken from Buckley *et al.* [43] to be 75% of the total N in the swine manure slurry (S.D. = 17%).

According to the Intergovernmental Panel on Climate Change (IPCC) guidelines [18], the emission factor for N_2O resulting from organic amendments application (EF_{N2O}) is 0.01 kg N_2O-N kg N^{-1}. Rochette et al. [44] estimated the cumulative C loss (as CO_2) due to swine slurry application to spring maize plots to be 63% of the original slurry C. In this study, the N and P leaching through the soil profile was assumed as 35% and 10% of manure N and P, respectively [22].

3. Results and Discussions

3.1. Impact Assessment

Table 6 presents a summary of the cumulative potential environmental impacts of the swine manure management scenario according to selected categories. Positive impact characterization values indicate an added environmental burden, while negative values represent avoided burden. Detailed descriptions are addressed in the following sections.

Table 6. Characterization of impacts for the proposed swine manure management scenario.

Impact Category	Unit	Proposed Swine Manure Management
Global warming (GWP 100-year)	kg CO_2-eq *	166
Fossil energy use	MJ	−57.9
Water use	m^3	−0.015
Marine eutrophication	kg N-eq	0.470
Aquatic eutrophication	kg PO_4^--eq	0.551

* eq Represents equivalent.

3.2. Global Warming Potential (GWP)

The proposed manure management scenario has net emissions of 166 kg CO_2-eq emitted per ton of swine manure slurry treatment. A detailed representation of the contribution of each stage to the cumulative GHG emissions is shown in Figure 2. Emissions during manure storage under slatted floors in the house and during external storage represented the majority of the GHG emissions, with the two stages contributing 42.1% and 35.1% respectively of the total emissions. This significant contribution is attributed to the high levels of N_2O and CH_4 emissions during these two steps, with both gases having a significantly higher impact on global warming potential. Similarly, the third-largest contributing stage to GHG emissions is post-separation slurry storage, i.e., 22.4% of scenarios of GWP.

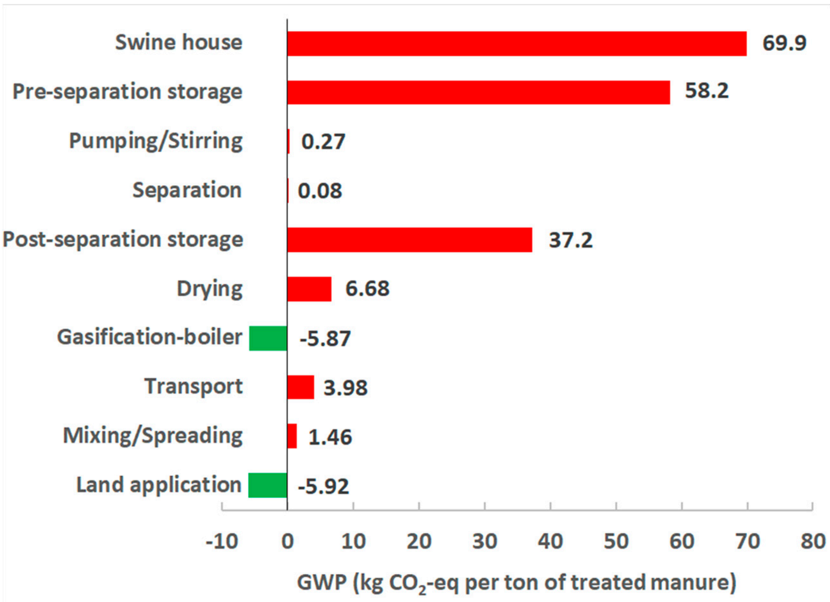

Figure 2. The net contribution of each stage to the cumulative global warming potential over 100 years (GWP 100a) in units of kg CO_2 equivalent (kg CO_2-eq). We used modified Intergovernmental Panel on Climate Change (IPCC, V1.02) [18] GWP factors embedded in the IMPACT World+ method [16].

Manure solids gasification and syngas combustion (in a boiler), represented as one coupled process (Figure 2), contribute - 3.54% of the total GWP. The net negative contribution here indicates that the avoided GHG emissions by syngas combustion, instead of natural gas, completely offset the combined emissions from syngas combustion and those associated with gasifier electricity consumption. Even though the low hot gas efficiency, 70%, and the low boiler efficiency, 78%, was used in this model, the overall ratio of avoided natural gas use resulted in a net negative GWP.

GWP for drying manure solids, 6.68 kg CO_2-eq, represented 4.02% of overall GWP emissions. Despite being an energy-intensive process, the low GWP contribution here for drying is attributed to the fact that the process heat is recycled from the gasification-boiler output heat, which reduces the overall energy requirement for drying and thus the impact. The following stages: pumping, stirring, separation, and transportation cumulatively contributed 3.49% of the total GHG emissions. Land application of liquid slurry and biochar, which is a co-product of thermal gasification, contributed net negative GHG emissions (- 5.92 kg CO_2-eq) due to the credit of displacing synthetic fertilizer. One thing to note is that CO_2 emission during land application is accounted for as biogenic CO_2 emission. The land application represents a 3.57% reduction of total GHG emissions.

3.3. Fossil Fuel Use

Cumulative fossil fuel energy use in this scenario was - 58.0 MJ per functional unit. Figure 3 details the individual contribution of manure management stages to overall fuel consumption. Manure storage steps, from an energy perspective, were all-passive and therefore had no fossil fuel expenditure or saving. The maximum energy burden was associated with the drying stage, which represented 62.0% of total fossil fuel energy input, followed by the slurry transportation stage, which represented 24.6% of total fossil fuel energy input. The gasification-boiler stage was attributed with the net negative energy use of - 95.7 MJ, by offsetting natural gas firing to produce the credited amount of thermal energy. The energy demand for the drying process, 107 MJ, represents the electricity demand in the dryer, which cannot be met through the gasification-boiler stage supply. The primary energy saving in this scenario, - 135 MJ, was attributed to the consequences of slurry-biochar land application. This savings is from the avoided synthetic fertilizers and the fossil fuel energy used in their production. For illustration, production of 1 kg N fertilizer requires 88.0 MJ of energy using global unit process of ecoinvent v3.4 database [16]. Similarly, production of 1 kg of P_2O_5 and K_2O require 20.1 and 18.4 MJ of fossil fuel energy in their production.

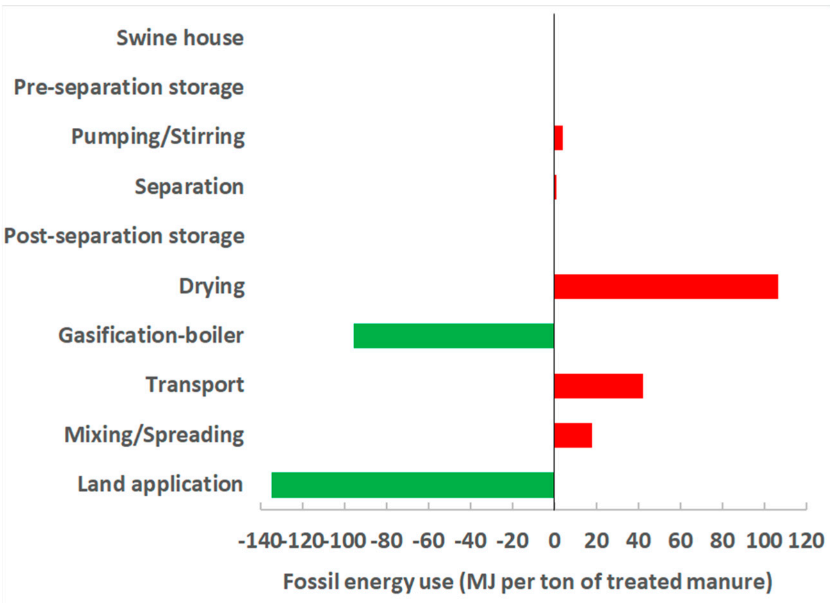

Figure 3. The net contribution of each stage to the cumulative fossil fuel energy use (MJ).

3.4. Water Depletion

This category indicates the total water use from different water sources: lakes, rivers, and wells. In this study, total water depletion was a process credit, i.e., avoided water depletion of 0.015 m^3 per functional unit. This credit is an indirect water-saving resulting from displacing synthetic fertilizers with the slurry-biochar mixture. The difference between land application impacts on water depletion, - 0.112 m^3, and total impact, 0.111 m^3, is attributed to all the energy-positive stages in the scenario. However, the savings accrued by displaced fertilizers outweighed the combined water depletion potential for these stages.

3.5. Marine Eutrophication

This mid-point impact category expresses the amounts of nutrients emitted, expressed in units of kg N equivalent, which potentially reach marine water causing eutrophic conditions. The studied scenario had a net positive (a burden) of marine eutrophication, 88.5% of which is attributed to the slurry-biochar land application. This results from nitrate (NO_3) leaching, and NH_3 emissions following land application. Considering the full lifecycle, 80% of marine eutrophication potential is attributed to NO_3 leaching, while the remainder is due to NH_3 emissions. The eutrophying effect of NH_3 occurs through the formation of acid rains that deposit back in water bodies causing N enrichment. Swine houses and pre-separation storage are together responsible for 5.7% of total marine eutrophication potential due to their NH_3 emissions.

3.6. Freshwater Eutrophication

Given that P is the limiting nutrient for most freshwater bodies, introducing P to rivers and lakes results in eutrophying conditions. In this study, 98.5% of total freshwater eutrophication potential is attributed to the impacts of slurry-biochar application. The leaching of 10% of P from the slurry is responsible for this impact.

3.7. Model Sensitivity to Thermochemical Conversion Parameters

To improve understanding of the implications of the proposed thermochemical conversion system (drying-gasification-boiler) on swine manure treatment, the conversion parameters, i.e., hot-gas efficiency (HGE) and boiler efficiency was varied to represent two additional alternatives. The first set represents low-efficiency conditions: HGE and boiler efficiencies at 60% and 68%, respectively. The second, a high-efficiency scenario, shows HGE and boiler efficiency at 80% and 88%, respectively. Figure 4 shows the impacts of the performance levels on the gasification-boiler stage. A 10% increase in the performance of both the gasifier and the boiler yielded a decrease in the GWP for this stage by 2.6 kg CO_2-eq (from 2.4 kg CO_2-eq to -0.2 kg CO_2-eq), and a corresponding increase in fossil fuel energy saving by 40.5 MJ (from -11.9 MJ to - 52.4 MJ). A 10% drop in the efficiencies increased GWP, from 2.4 to 4.6 kg CO_2-eq, and a change from a fossil fuel energy use of -11.9 MJ to an energy expenditure of 23.5 MJ. The non-linear response in the efficiency scenarios is because the overall efficiency for the gasification-boiler is the product of the conversion and the boiler efficiencies. No noticeable changes were observed in the other impact categories with changes in the efficiencies.

For the full treatment system, increasing the thermochemical conversion efficiency by 10% relative to the baseline led to a 1.5% decrease in GWP and an increase of the fossil fuel savings of 52.4 MJ. These findings suggest that the range of sensitivity for the thermal conversion system has a marginal impact on the GWP for the entire management scenario. It is worth noting, however, that the combined GWP for the separation, drying, and gasification-boiler stages, 0.89 kg CO_2-eq, is lower than the difference in GWP between pre-separation storage, 58.2 kg CO_2-eq, and post-separation storage, 37.3 kg CO_2-eq. The separation-drying-gasification-boiler combination can be considered an emission reduction measure for manure storage. From an energy perspective, the gasification system has a beneficial impact on the total energy use in manure management, notwithstanding high energy requirements for drying. Improvements to thermal conversion efficiency (gasification and syngas firing) combined with improvements to the drying technology can significantly improve the overall environmental performance for swine manure management via thermochemical conversion.

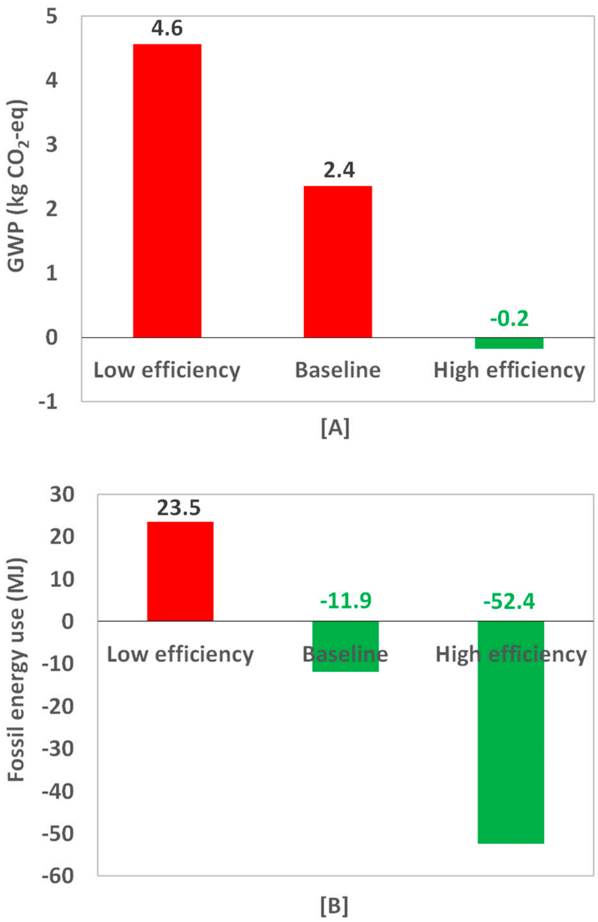

Figure 4. Impacts of gasification-boiler performance on (**A**) global warming potential (GWP 100a), and (**B**) fossil fuel energy use (MJ).

4. Implications of the Study

The findings in this investigation contribute to the ongoing discussion on manure management best practices. Given the swine manure composition and the management techniques practiced on the farm, the thermochemical conversion is a challenging technique to dispose of wet swine manure. Improvements to the solid-liquid separation system that reduces moisture content in solid fraction can potentially improve the environmental process of the proposed system.

From GHG emissions and energy use perspectives, the land application step of swine manure management appears beneficial due to the credits from replacing synthetic fertilizer consumption. However, in regions of intensive swine production where manure land application regulations are strict, thermochemical conversion can be an alternative approach to utilize manure. Adopting innovative sludge drying technologies, i.e., biodrying technology [16], can significantly reduce the drying energy demand, and consequently, the GHG emissions. Also, more studies towards a better understanding of biochar agronomic value could potentially help in incentivizing the thermochemical conversion of swine manure solids.

5. Conclusions

- Swine manure liquid storage (before and after solid-liquid separation) contributed 57.5% of the GHG emissions for the entire proposed manure management scenario.
- Swine manure solids separation, drying, and gasification resulted in a net energy expenditure of 12.3 MJ for each functional unit (treatment of 1 metric ton of manure slurry).
- The high energy demand associated with manure drying represented greater energy requirement than the energy produced from the gasification/boiler stage.
- Land application of slurry-biochar mixture is credited with 5.9 kg CO_2-eq in avoided GHG emissions, and 135 MJ of avoided fossil fuel energy use resulting from avoided synthetic fertilizer production.
- Improvements to drying and thermochemical conversion efficiencies may further significantly reduce fossil fuel use in thermochemical manure management.

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