Environmental sustainability performance of a membrane-based technology for livestock wastewater treatment with nutrient recovery

I. Gonz´alez-García a[, B. Rian˜o](#_bookmark0) a[, R.M. Cu´ellar-Franca](#_bookmark0) b[, B. Molinuevo-Salces](#_bookmark1) a[, M.C. García-](#_bookmark0)

Gonza´lez [a,](#_bookmark0)[\*](#_bookmark2)

a *Agricultural Technological Institute of Castilla y L*´*eon, Ctra. Burgos, km. 119, 47071 Valladolid, Spain*

b *Department of Chemical Engineering, The University of Manchester, The Mill, Sackville Street, Manchester M13 9PL, UK*

*Keywords:*

Life cycle assessment Manure treatment Ammonia reduction Nutrient imbalance Agricultural effluents

A B S T R A C T

The gas-permeable membrane (GPM) technology is one of the most novel techniques capable of minimizing ammonia (NH3) emissions associated to wastewaters, while recovering nitrogen as nutrient. This study con- ducted for the first time a life cycle assessment of this technology (treatment scenario), to compare the envi- ronmental trade-offs with the conventional manure management (conventional scenario), and determine which strategy performs better. The environmental impact results per m3 of manure, estimated using the ReCiPe method V 1.1, indicated that the treatment scenario reduces global warming (GW) by 14% and marine eutro- phication (ME) by 32% with respect to the conventional scenario, whilst it increases particulate matter formation (PMF) and terrestrial acidification (TA) by 16% and 17%, respectively, due to some NH3 volatilization. Other impact categories considered were ozone formation (affecting human health (HOF) and ecosystems (EOF)), where the treatment scenario was able to reduce this impact by 48% and 50%, respectively. For freshwater eutrophication (FE), the net value was similar for both scenarios. A sensitivity analysis looking at optimum membrane design parameters (optimized treatment scenario) resulted in further reductions between 26% and 86% for GW, ME, PMF and TA with respect to the conventional scenario, although one potential drawback is the application of higher amount of phosphorous with the organic fertilizer, which resulted in higher FE impacts. Overall, the GPM system-based treatment is more environmentally sustainable compared to the conventional scenario thus making this an attractive option for environmental management systems, especially in areas with low water quality or high nutrient imbalance.

# Introduction

Ammonia (NH3) emissions have been described as ones of the most harmful pollutants, which can lead to environmental problems such as acidification, eutrophication and particulate matter formation (PMF), affecting ecosystem and human health [[1]](#_bookmark14). The agricultural sector contributes with 93% of NH3 emissions in the EU, and the majority of these emissions comes from livestock waste [[2]](#_bookmark15). Manure storage and spreading into land, as organic fertilizer, is a well and long-established practice in the agri-food industry [[3,4]](#_bookmark16). It has been recognized as a viable alternative to mineral fertilizers, and it is in line with the prin- ciples of circular economy [[5]](#_bookmark17). The common management practice for manure use as organic fertilizer consists on its storage in uncovered lagoons before spreading to fertilize agricultural fields [[6]](#_bookmark18). However, this practice is associated with several environmental issues due to the

production and release of gase emissions such as methane (CH4) nitrous oxide (N2O) and NH3 [[7]](#_bookmark19). It also contributes to a surplus generation of nutrients such as nitrogen (N) and phosphorous (P), leading to consid- erable environmental damage due to leaching to water bodies [[8,9]](#_bookmark20). To address these issues, current EU policies and more recently the Farm to Fork strategy [[8]](#_bookmark20), aim to provide farmers with a framework for imple- menting measures to reduce pollutant emissions and improve nutrient efficiency [[1]](#_bookmark14). Further, the strategy enhances to adopt innovative tech- niques and sustainable agricultural practices, particularly in areas with intensive livestock activities. Therefore, there is a need to develop and implement technologies for manure treatment, that allow minimizing the environmental issues and the safe redistribution of nutrients back to the soil, while maintaining the competitiveness of the livestock sector. Techniques for nutrient recovery have become of particular interest over the last years, due to the environmental and economic advantages

that this practice has to offer [[10]](#_bookmark21). Different techniques have been studied and applied for recovering N from livestock wastewater, including ammonia stripping [[11]](#_bookmark22), zeolite adsorption through ion ex- change [[12]](#_bookmark23), struvite precipitation through co-precipitation with phos- phate and magnesium [[13]](#_bookmark24), and more recently, gas-permeable membrane (GPM) technology [[14]](#_bookmark25). The latter presents several technical advantages with respect to the other existing technologies. For example, the GPM technology operates at lower pressures, and it avoids the use of alkali substances [[15]](#_bookmark26). This technology has been studied from an eco- nomic and energetic point of view, and it is considered one of the most energy efficient and cost-effective technology for the recovery of N [[16,](#_bookmark27) [17,18]](#_bookmark27). Nevertheless, the environmental performance of this technology is yet to be assessed.

In the GPM technology, the NH3 present in the wastewater passes through a microporous hydrophobic membrane via diffusion, i.e. a tubular GPM is submerged in the wastewater. The NH3 is captured by the trapping solution and recovered as valuable ammonium sulfate so- lution, which is easy to store and safe for users. This technology has been successfully applied to recover N from livestock waste and anaerobic digestate at laboratory scale [[19,20,21]](#_bookmark29), and more recently, Molinuevo-Salces et al. [[10]](#_bookmark21) reported the application of the GPM tech- nology on a pilot-scale plant to recover N from swine manure, achieving a good technical performance. The GPM technology is regarded as one of the best technologies reported in the literature for recovering N from livestock wastewater [[17]](#_bookmark28).

Different agricultural residue management strategies have used life cycle assessment (LCA) to ensure a transition into more sustainable practices [[22]](#_bookmark30). For example, several LCA studies on swine manure management technologies have been carried out to quantify and compare the environmental burdens and potential benefits of these systems [[23,24,25]](#_bookmark31). Other studies, such as Brockmann et al. [[26]](#_bookmark34) and Hoeve et al. [[27]](#_bookmark35), went beyond this scope to consider the avoided environmental impacts of the recovered nutrients, in order to determine their energy and resource efficiencies relatively to that of manufactured mineral fertilizers. For instance, these studies looked at replacing min- eral fertilizers using manure as organic fertilizer, and bio-based fertil- izers recovered as by-products in manure treatments [[26,27]](#_bookmark34). However, according to Gontard et al. [[28]](#_bookmark36), the lack of reliable inventory data is a major limitation of LCA applied in the assessment of agricultural waste management systems.

To the best of our knowledge, this study presents the first environ- mental sustainability assessment of this GPM technology. In this work, an operating swine manure treatment pilot plant employing this tech- nology in a farm in Spain is used as reference. The environmental per- formance of the GPM technology is compared with the conventional management option, i.e. storage and land application of swine manure. The primary inventory data used in this LCA study has been sourced directly from the farm site, thus relying on representative data, an added value to this work. Special consideration was given to NH3, NOx and NO - emissions due to the relevance of N compounds in the agricultural sector.

3

The application of LCA at early stages of the technological devel- opment will provide a better understanding of the underlying environ- mental implications of deploying this technology, and therefore, prevent burden shifting across other environmental impact categories. The findings from this work will be of interest to various stakeholders in the agri-food and waste management sectors, as the GPM technology can be applied to treat different ammonia-containing wastewaters [[14]](#_bookmark25), as well as end-users and policymakers seeking for more sustainable waste management and nutrient valorization practices addressing nutrient imbalance issues.

The next section discusses the methodology applied here including the goal and scope definition, inventory analysis and description of the scenarios studied here. [Section 3](#_bookmark7) presents the results obtained for both scenarios, including a discussion around all environmental impacts considered, a sensitivity analysis, a comparison with other studies for

validation, and limitations and recommendations. Finally, the conclu- sions are presented in [Section 4](#_bookmark13).

# Materials and methods

The environmental sustainability assessment of the swine manure treatment plant with GPM technology option and the conventional management practice was conducted using the ISO 14040 and 14044 LCA methodology [[29,30]](#_bookmark37), in combination with the recommendations from UNEP/SETAC [[31]](#_bookmark38). The study followed the attributional approach, which provides information about the impacts of the processes related with the production, consumption and disposal of the systems under study [[32]](#_bookmark39). The Open LCA software V 1.10 [[33]](#_bookmark40) was used to conduct the LCA modeling. The next sections provide a detailed description of the assessment.

* 1. *Goal and scope*

The goal of this study was to evaluate the potential life cycle envi- ronmental impacts of the application of the innovative GPM technology, for the treatment of swine manure for NH3 reduction and N recovery as ammonium sulfate solution, which will be referred to as the “treatment scenario”, and compare it with the current practice or “conventional scenario”. The “conventional scenario” consists of storing the manure without any further treatment and used as fertilizer in agricultural fields. The comparison provides information regarding the environ- mental trade-offs between the two management scenarios. Main op- portunities for improving the environmental performance of the GPM technology were also identified using a hotspot analysis.

The study is based on an existing pilot treatment plant located in a sow farm in Guardo, Palencia (north of Spain). A full description of the pilot plant can be found in Molinuevo-Salces et al. [[10]](#_bookmark21). The system under study considered the storage and treatment of the swine manure, transport and application of the resources produced, e.g. organic and liquid fertilizers, and their end-of-life, e.g. emissions to air and soil, as shown in [Fig. 1](#_bookmark4) and [Fig. 2](#_bookmark5) for the “conventional” and “treatment” sce- narios, respectively. The full description for each scenario is presented in [Section 2.2](#_bookmark3).

Both scenarios were credited with the production of organic fertil- izer, and the treatment scenario was also credited for the production of ammonium sulfate solution. The credits are given for displacing the equivalent amount of mineral fertilizer based on their corresponding nutrients levels. All upstream activities were excluded from this study as it can be assumed that these will be the same for both management options [[25]](#_bookmark33).

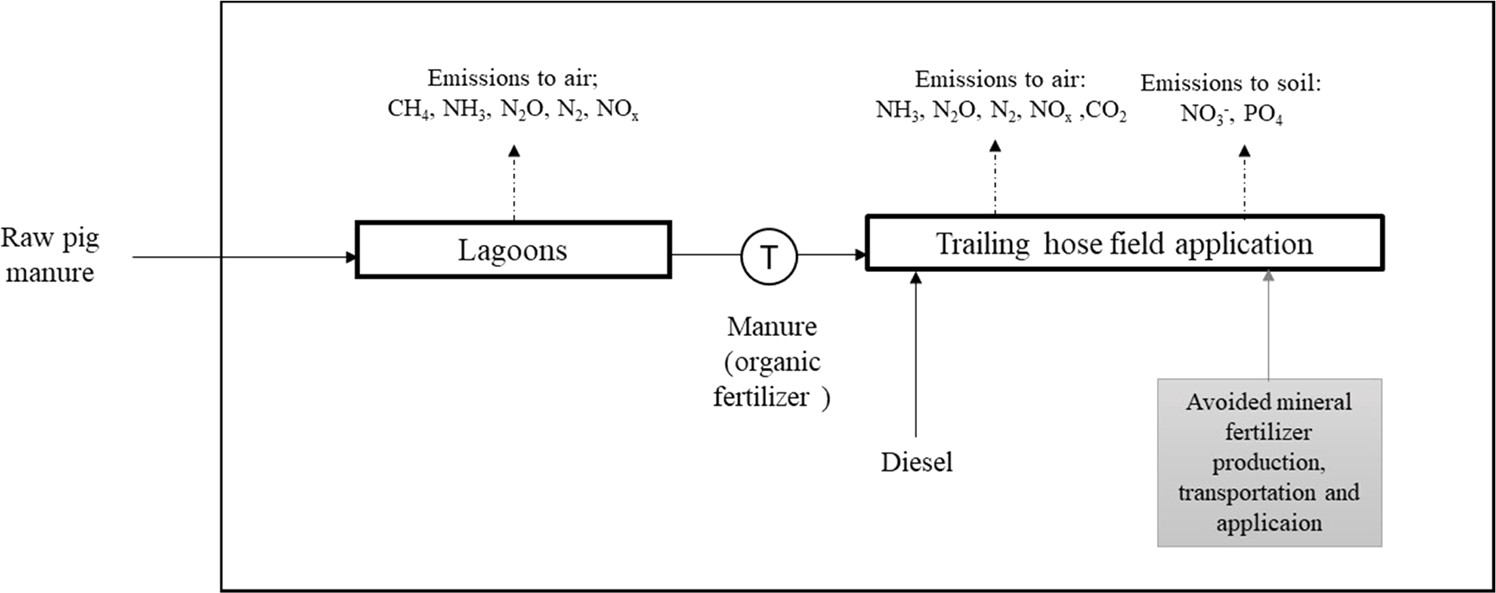
The functional unit was defined as the “management of one cubic meter of manure excreted by pigs”, as commonly considered in nutrient recovery studies [[34]](#_bookmark41).

* 1. *Inventory data and assumptions*

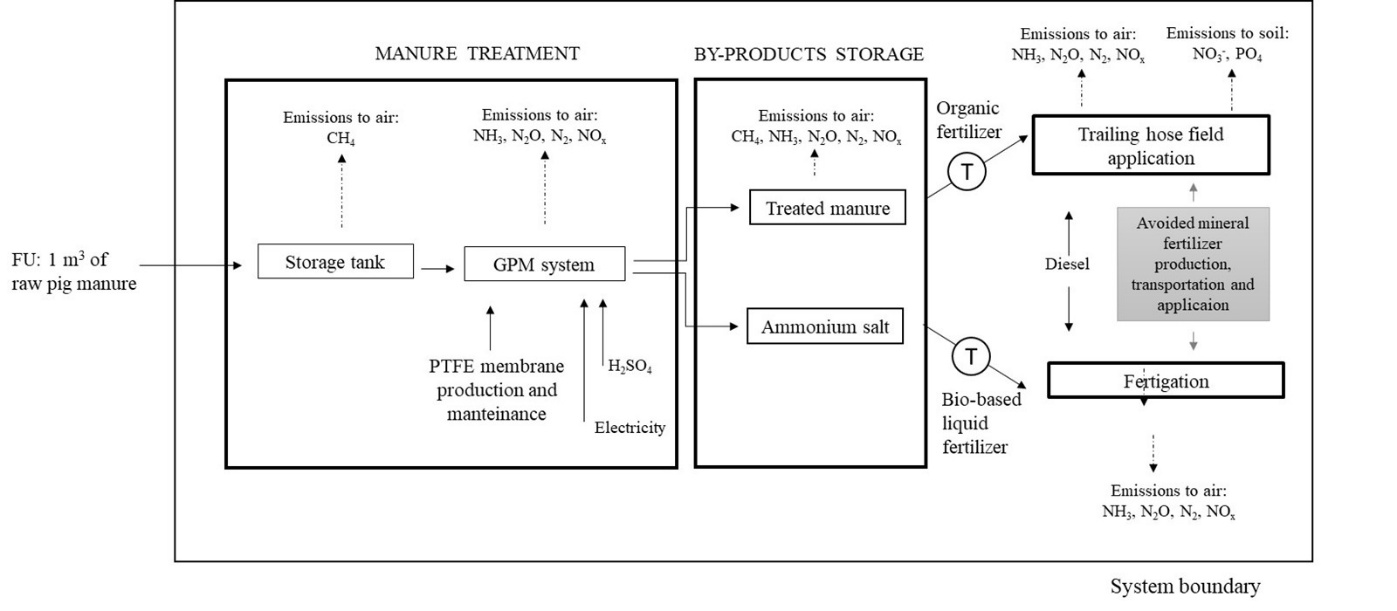
The primary inventory data for the treatment scenario has been obtained from an operating pilot plant located in a farm in Guardo, in the North of Spain as previously mentioned. For the conventional sce- nario, data have been obtained from calculations based on annual manure production volumes at the farm and the nearby fields. Addi- tional inventory data have been sourced from literature and relevant databases: Ecoinvent 1.10 [[35]](#_bookmark42), Agribalyse V3 [[36]](#_bookmark43), ELCD 3.2 [[37]](#_bookmark44),

Environmental Footprint 2.0 [[38]](#_bookmark45).

The sow farm considered in this study generates around 17,136 m3 of swine manure every year, which was taken as the basis for this study. The chemical characterization of the manure is presented in Table S1 in Supplementary materials, which were used for assessing both scenarios. The calculations and the assessment were considered for a full year of treatment operation. Specific seasonal data was not considered here as seasonal changes in emissions levels are negligible [[39]](#_bookmark46). The description



**Fig. 1.** System boundaries for the conventional scenario. [Transport (T)].

**Fig. 2.** System boundaries for the treatment scenario using GPM technology. [Transport (T); polytetrafluoroethylene (PTFE)].

of the life cycle stages and data used for assessing both scenarios are described in the next sections.

* + 1. *Conventional management*

The conventional scenario comprises three main stages ([Fig. 1](#_bookmark4)). First, the raw manure is stored on-farm in uncovered lagoons for a period of six-months. This is followed by the transport of the manure to the spreading area, where it is applied into cropland as organic fertilizer by trailing hose, thus replacing mineral fertilizer.

The emissions released to the atmosphere from the lagoons during the storage are presented in Table S2 of Supplementary materials. Only anthropogenic sources of carbon dioxide (CO2) were considered in this study as CO2 emissions from manure can be classified as biogenic car- bon, hence assumed to be zero [[40,41]](#_bookmark47).

* + 1. *GPM treatment management*

The treatment scenario consists of five stages ([Fig. 2](#_bookmark5)). First, the raw manure is stored on-farm in a closed storage tank. The manure is then fed to the GPM system in order to recover the NH3 content in the form of ammonium sulfate solution. The treated manure, which contains a lower total ammonia nitrogen (TAN) concentration, and the ammonium sul- fate solution, are stored onsite and they are used as fertilizers when required. The treated manure passes from the GPM system to storage by gravity, and the same happens for the trapping solution, therefore there is no energy consumption in the by-products storage stage. The treated manure is transported and applied as organic fertilizer, whilst the ammonium sulfate solution is transported to fields and used for its application.

The GPM system is equipped with a manure feeding pump, an NH3 separation reactor tank that contains the membrane panels, an aeration pump, a manure recirculation pump used for mixing in the reactor, a tank containing the trapping solution (1 N H2SO4), a pump for recircu- lating the trapping solution through the membrane and a heating blanket [[10]](#_bookmark21). The tubular membrane is made of expanded polytetra- fluoroethylene (e-PTFE). The raw manure is pumped from the storage tank to the NH3 separation reactor tank. Once the reactor tank is full with swine manure, the tank is aerated to increase the pH, thus con- verting ammonium (NH +) into NH . The NH passes through the membrane system where is being captured and concentrated in a trap- ping solution on the other side of the membrane. The resulting product is an ammonium sulfate solution. The manure is recirculated to keep a homogeneous mixture.

The findings reported in Molinuevo-Salces et al. [[10]](#_bookmark21) for the GPM pilot-scale study were used to establish the following assumptions. The GPM system operated in batch mode, and the raw manure had a resi- dence time of seven days in the NH3 separation reactor tank. In this work, a TAN removal of 34% was achieved, of which 62% was recovered in the trapping solution. Negligible P removal was considered in this study. The final TAN concentration in the ammonium sulfate solution was 20.7 kg N/m3, with a total production of ammonium sulfate of 30 L/m3 of manure.

4 3 3

For each cubic meter of manure treated, around 0.05 m2 of mem- brane area was needed. It was assumed that during one year of opera- tion, it was necessary to replace 10% of the membrane for maintenance. This amounts to 2.82 g of polytetrafluoroethylene (PTFE) granulate (density of 2.16 g/cm3), and PTFE production data was sourced from the Environmental Footprint 2.0 database [[38]](#_bookmark45). The amount of sulfuric acid (98%) needed for TAN capture was estimated at 4.39 kg/m3 of manure

and the background data for this process was sourced from the Ecoin- vent database V1.10 [[35]](#_bookmark42).

The energy requirements of the GPM system were monitored using a power grid analyzer and the resulting electrical consumption was esti- mated at 28 kWh/day or 39.2 kWh/m3 of manure. Electricity is used for aeration, recirculation and for heating. The Spanish electricity mix for 2018 was used here [[42]](#_bookmark48).

* + 1. *Transportation stage*

The assumptions and calculations made for the transportation stage apply to both scenarios. The raw and the treated manure resulting from the conventional and the treatment scenarios, respectively, were trans- ported from the farm to the receiving areas for application on local fields. A travel distance of 3.5 km in a tractor equipped with a 25 m3 payload was assumed. The tractor’s fuel consumption was estimated at

2.49 L of diesel/m3 of manure [[25]](#_bookmark33). The treatment scenario also pro- duces an ammonium sulfate solution, which was assumed to be trans- ported over 25 km from the farm to the designated crop field in a lorry equipped for liquid transport. The diesel consumption and emissions were sourced from the Ecoinvent database V1.10 [[35]](#_bookmark42). The GPM system included the transportation of sulfuric acid needed for treating 1 m3 of raw manure. The data for calculating diesel consumption and emissions released were sourced from the Ecoinvent database V1.10 [[35]](#_bookmark42), assuming a transportation distance of 100 km between the production site to the treatment plant.

* + 1. *Field application stage*

It was assumed that the application of organic fertilizers was carried out using a trailing hose for both scenarios, and the application of the ammonium sulfate solution, resulting from the treatment scenario, was done through spraying. The calculated emissions to the atmosphere and soil resulting from these activities are presented in Table S2 (Supple- mentary materials). Biogenic CO2 emissions were excluded from this study as explained in [Section 2.2.1](#_bookmark6).

Emissions derived from the machinery used during field application of organic fertilizers in both scenarios, and for the ammonium sulfate application produced in the treatment scenario, were estimated using the Ecoinvent database V1.10 [[35]](#_bookmark42). The diesel consumption was esti- mated at 0.023 kg of diesel/m3 of manure, which was based on the crop field surface embraced. Overlapping during field work was considered. No other particulate matter besides from combustion activities were considered here.

It was assumed that the organic fertilizers and the ammonium sulfate solution produced in the scenarios replaces the production and appli- cation of mineral fertilizers such as diammonium phosphate (as P2O5), urea ammonium nitrate (as N), and ammonium sulfate (as N) in a ryegrass field (crop yield of 5 tonnes per hectare and a N requirement of 22 kg per tonne [[43]](#_bookmark49)). The equivalent amounts of displaced mineral fertilizer were estimated based on the amounts of basic nutrients (N and P) needed for the crop production. Assuming a N and P efficiency of 60% and 100% for the raw and treated manure, respectively, the amounts of avoided fertilizer were estimated at 1.44 kg of P2O5 and 5.34 kg of N for the conventional scenario and 1.44 kg of P2O5, 3.93 kg of N and 2.95 kg of N for the treatment scenario. The ammonium sulfate produced in the treatment scenario can avoid the use of 2.95 kg of mineral ammonium sulfate (as N). Crop residues were excluded here as it falls outside the scope of this study. Other emissions associated with swine farming such as microbes, antibiotics, hormones and heavy metals were excluded as their potential impacts are currently not quantifiable in LCA [[27]](#_bookmark35). The study also excluded the impacts associated with odor emissions as there is no consensus around the quantification of these type of emissions [[44,](#_bookmark50) [45,46]](#_bookmark50).

*Environmental impact assessment*

The LCA modeling was carried out using the Open LCA V1.10 soft- ware [[33]](#_bookmark40) and the environmental impacts were estimated using the updated version of the ReCiPe 2016, V1.1, impact assessment method (Goedkoop et al., [[47,49]](#_bookmark51)), at midpoint level, and assuming a hierarchist perspective. The following seven midpoint impact categories, which reflect the environmental issues related to the system under study, were estimated: global warming (GW), fine particulate matter formation (PMF), freshwater eutrophication (FE), marine eutrophication (ME), ozone formation (human health (HOF) and terrestrial ecosystems (EOF)) and terrestrial acidification (TA).

# Results and discussion

This section presents and compares the environmental impact results of the conventional and treatment scenarios, including a sensitivity analysis and comparison with other LCA studies of swine manure treatment reported in literature. The major outcomes, limitations and recommendations for improvement are discussed at the end of this section.

* 1. *Environmental impacts*

The environmental impact results are presented in [Fig. 3](#_bookmark8) for the conventional scenario and in [Fig. 4](#_bookmark9) for the treatment scenario. The midpoint impact results and a breakdown contributions per stages can be found in Table S3 (Supplementary material).

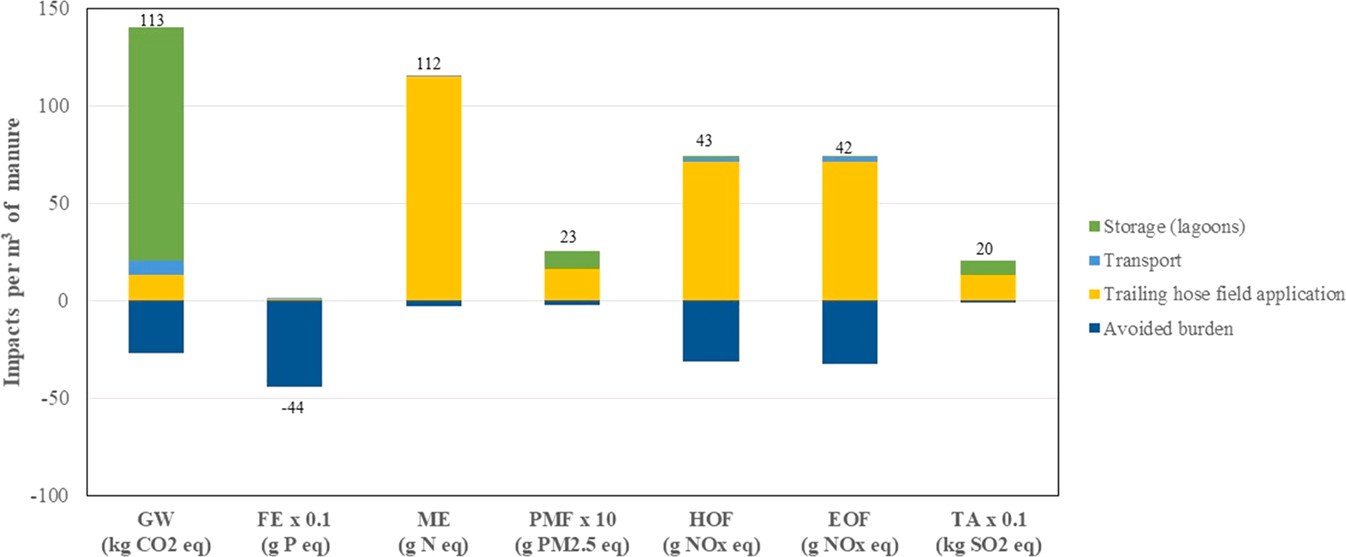
* + 1. *Global warming (GW)*

The total net impact for GW of the conventional scenario was esti- mated at 113 kg CO2 eq./m3 of manure, with the manure storage stage contributing with 85% of the total impact ([Fig. 3](#_bookmark8)). This is mostly due to CH4 emissions and in less extent to the N2O emissions generated during the storage in the uncovered lagoons. The application of the manure as organic fertilizer accounted for 9% of the total impact, where the emissions of N2O from raw manure were the main contributors. The transportation stage contributed with the remaining 5% of the total impact. The production of organic fertilizer displaced the production and use of mineral fertilizer (on a nutrient equivalent basis), thus crediting the system and reducing GW by 19% ([Fig. 3](#_bookmark8)).

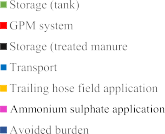
The total net GW for the treatment scenario was estimated at 97 kg CO2 eq./m3 of manure, with the storage of the treated manure contributing with 64% of the total impact ([Fig. 4](#_bookmark9)). The main contribu- tors from this stage were the CH4 and N2O emissions from the treated manure. This was followed by the GPM system with 16% of the total impacts, mainly due to the energy consumption, and the N2O emissions from manure. The GPM system was the only stage of the treatment process where electricity is required (for aeration, pumping and heat- ing). The trailing hose spreading accounted for 8% of the total GW, where N2O emissions from manure were identified as the main con- tributors from this stage. The initial storage stage contributed only with 6% of the GW impact, mainly because of the direct CH4 emissions from manure. The transport of the treated manure and the transport of the ammonium sulfate contributed with 6% to the total impact. However, manure transportation accounted for the large majority (5%) of the impacts estimated for this stage as a greater amount of manure was transported (1 tonne per m3 of manure) with respect to ammonium so- lution (53.1 kg per m3 of manure). Contributions from the application of the ammonium sulfate stage were negligible. Similar to the conventional scenario, credits were given for displacing an equivalent amount of mineral fertilizer for the production of organic fertilizer and ammonium sulfate, leading to an overall reduction of 22% of the total GW ([Fig. 4](#_bookmark9)).

The GW impacts of the treatment scenario are 14% lower compared

to the conventional scenario. This is in part due to better manure storage practices, e.g., closed tanks, that allowed the reduction of direct CH4 and



**Fig. 3.** Life cycle environmental impacts for the conventional scenario per m3 of manure. [The values of some impacts have been scaled to fit. To obtain original values, multiply total values by the scaling factor on the x-axis. Impact categories: global warming (GW); freshwater eutrophication (FE); marine eutrophication (ME); fine particulate matter formation (PMF); ozone formation (human health, (HOF) and terrestrial ecosystems, (EOF)); terrestrial acidification (TA)].





**Fig. 4.** Life cycle environmental impacts for the treatment scenario per m3 of manure. [The values of some impacts have been scaled to fit. To obtain original values, multiply total values by the scaling factor on the x-axis. For impacts nomenclature see [Fig. 3](#_bookmark8)].

N2O emissions, as well as N recovery, which was able to offset some of the contributions from operating the GPM system, e.g., energy re- quirements and raw materials. Therefore, the treatment scenario rep- resents a better option to the conventional scenario from a global warming perspective.

* + 1. *Freshwater eutrophication (FE) and arine eutrophication (ME)*

The total net FE results for the conventional and treatment scenarios were estimated at — 4.35 and — 4.39 g P eq./m3 of manure ([Figs. 3 and](#_bookmark8) [4](#_bookmark8), respectively). Whilst both scenarios resulted in net negative impacts due to the displacement of mineral fertilizer, P leaching during the application stage was the main contributor in both cases. However, such contribution was significantly higher for the treatment scenario as higher amounts of treated manure as organic fertilizer per surface area are required based on N crop demand. This is because the GPM tech- nology reduces manure’s N levels without altering P levels and as the amount of treated manure applied increases, so does the potential amount of leached P.

The total net ME was estimated at 112 g N eq./m3 of manure for the conventional scenario ([Fig. 3](#_bookmark8)) and 76 g N eq./m3 of treated manure for the treatment scenario ([Fig. 4](#_bookmark9)), with the trailing hose field application stage contributing with the large majority (99%) of these impacts for both scenarios, and this is due to nitrate leaching. However, the total ME in the treatment scenario is 32% lower compared to the conventional scenario because of the lower N levels in the organic fertilizer as pre- viously explained, thus reducing the amount of NO3- leached from spreading the treated manure (or organic fertilizer).

From these results, it can be inferred that the GPM system can notably reduce eutrophication issues directly associated with N leach- ing, e.g. ME impacts; however, excess of P emissions represents a po- tential risk as shown in the FE impacts results, and the P content in

organic fertilizer should also be monitored and controlled to prevent nutrient saturation of freshwater bodies.

* + 1. *Fine particulate matter formation (PMF)*

The total net PMF for the conventional scenario ([Fig. 3](#_bookmark8)), was esti- mated at 231 g PM2.5 eq./m3 of manure, whilst for the treatment sce- nario this was calculated at 269 g PM2.5 eq./m3 of manure, which is 16% higher. This is mostly due to some NH3 volatilization occurred during the manure treatment by the GPM system, because of the increment of the pH of the manure, as NH3 is a precursor for particulate formation [[1]](#_bookmark14). The major hotspots in the conventional scenario were the applica- tion stage (63%) and the storage in the open lagoons (37%), whilst for the treatment scenario, the main contributors were the application stage (37%), the GPM system (36%) and the storage of the treated manure (22%). The ammonium sulfate application stage contributed with 5% to the total impact. Whilst the contribution from the application stage was reduced for the treatment scenario by 32% due to the N content reduction from manure in the GPM system, it can be observed that some of these emissions were shifted to the manure treatment stage (e.g. GPM technology), and the ammonium sulfate application stage. Contributions from transport were negligible and no contributions were attributed to the raw manure storage stage as it was stored in a closed tank.

The losses of NH3 due to volatilization during the application of the

GPM technology represents an opportunity for improvement which has been explored through a sensitivity analysis and discussed in [Section](#_bookmark10) [3.2](#_bookmark10).

* + 1. *Ozone formation (Human health (HOF) and terrestrial ecosystems (EOF))*

Similar trends can be observed in [Figs. 3 and 4](#_bookmark8) for both HOF and EOF impact categories. The total net HOF and EOF for the conventional

scenario were estimated at 43 g NOx eq./m3 of manure and 42 g NOx eq./m3 of manure, respectively, and for the treatment scenario, these impacts were calculated at 22 g NOx eq./m3 of manure and 21 g NOx eq./m3 of manure, respectively.

In the case of the conventional scenario, the higher impact was produced during the trailing hose application stage, with 96% (for both HOF and EOF impact categories), due to NOx emissions. Transport contributed with 2% of the impact, also due to NOx emissions.

In the treatment scenario the trailing hose field application stage was responsible for 95% of the impacts due to the NOx emissions, although in this case the treatment reduced those to 53 g NOx eq./m3 of manure. Transport contributed with a total of 4%, with manure transportation accounting for the large majority of these. Contributions from the GPM system are considered negligible, i.e. around 1% due to NOx emissions from raw materials transport.

The treatment scenario presents an impact reduction of 49% of g NOx eq./m3 of manure for the HOF category and 50% impact reduction of g NOx eq./m3 of manure for the EOF category.

Also, the treatment scenario presented 10% higher avoided impacts for these two impact categories than the conventional scenario, indi- cating that the GPM technology is a viable manure management option.

* + 1. *Terrestrial acidification (TA)*

The total net TA for the conventional and treatment scenarios were estimated at 1.95 kg SO2 eq./m3 of manure and 2.29 kg SO2 eq./m3 of manure, respectively. The total net TA for the treatment scenario is 17% higher with respect to the conventional scenario, mostly due to some volatilization of NH3 as consequence of the pH increase during the treatment. The contributions by stages in this impact category followed a very similar pattern to the one reported for PMF, as NH3 emissions are responsible for the majority of these contributions. For example, the application stage and storage in open lagoons in the conventional sce- nario contributed with 62% and 38% of the total net TA, respectively. For the treatment scenario, the GPM system and the trailing hose application accounted for 37% each of the total impacts due to NH3 emissions from manure. The storage of the treated manure contributed with 22% of the total TA, and the ammonium sulfate application contributed with the remaining 5% of the total TA. Emissions from transport were negligible.

The potential improvements for the treatment scenario through a higher ratio of membrane surface per volume of swine manure were assessed in a sensitivity analysis presented in [Section 3.2](#_bookmark10).

* 1. *Sensitivity analysis*

A sensitivity analysis was performed for the treatment scenario to explore the assumptions made around the design of the GPM system in an effort to reduce NH3 emissions, which was identified as one of the major issues associated with the operation of the GPM technology. It has been reported that higher TAN removal and recovery efficiencies can be achieved by increasing the ratio of membrane surface per volume of swine manure [[10]](#_bookmark21). Therefore, a higher ratio of membrane surface was considered based on García-Gonza´lez et al. [[19]](#_bookmark29), where a ratio of membrane surface per volume of manure of 0.013 m2/L was considered. This ratio is around four times higher than the one considered in the treatment scenario (0.003 m2/L).

Under these new specifications, it was assumed that a TAN removal of 85.1% with a TAN recovery of 99.0% were achieved after 7 days of treatment. The quantity of membrane needed in the optimized GPM system was estimated at 0.24 m2 per m3 per year, which is around five times higher compared to the pilot plant in the treatment scenario. It was assumed that 10% of the membrane used was replaced every year. The TAN concentration in the ammonium sulfate solution was estimated at 78 kg N/m3 and the quantity of ammonium sulfate solution produced was 30 L/m3 of manure. The total amount of H2SO4 (98%) needed for TAN capture was calculated at 7.93 kg/m3 of manure. The amount of

displaced mineral fertilizer was estimated at 1.44 kg of ammonium phosphate/m3 of manure and 1.65 kg urea/m3 of manure.

The environmental impact results of the optimized treatment sce- nario are shown in [Fig. 5](#_bookmark11). As can be observed, the optimized treatment scenario showed further reductions with respect to the treatment and conventional scenarios for all impact categories except for FE.

The total net GW of the optimized treatment scenario was estimated at 83 kg CO2 eq./m3 of manure, which is 14% lower compared to the treatment scenario and 26% lower than the conventional scenario ([Fig. 5](#_bookmark11)). This was mainly due to the reductions in N2O emissions from land spreading of the treated manure as a consequence of the reduction of N content in the treated manure.

For ME, the total net impact was calculated at 16 g N eq./m3 of manure which was between 80% and 86% lower than the treatment and conventional scenarios, respectively. This was largely due to the higher N removal rates achieved with the optimized GPM system, thus reducing NO3- leaching during land spreading.

A notable reduction of 74% for the optimized treatment scenario can be observed for the PMF impact with respect to the conventional sce- nario ([Fig. 5](#_bookmark11)), where the impact of the trailing hose application impact was reduced from 161 g PM2.5 eq./m3 of manure to 51 g PM2.5 eq./m3 of manure. This is mainly due to the reduction in the NH3 and N2O emis- sions in the system by the GPM treatment. The optimized treatment scenario reduced the PMF impact by 78% compared with the treatment scenario. Nevertheless, the contributions from the ammonium sulfate application stage increased in the optimized treatment scenario because of an increase in NH3 emissions resulting from a more concentrated ammonium sulfate solution. This hotspot should be taken into account in order to improve the application of this treatment option.

For the HOF and EOF categories, the direct impact of the optimized treatment scenario resulted in final negative values of — 35.5 and

— 37.1 g NOx eq./m3 of manure for HOF and EOF, respectively, due to

the avoided impacts from replacing mineral fertilizers. Similarly to the conventional and treatment scenarios, the major contributor was the trailing hose application stage with contributions of 75% for both HOF and EOF, which represents reduction of 78% and 76% compared with the treatment scenario, and a reduction of 83% and 84% compared with the conventional scenario.

For TA impact category, the optimized treatment scenario presented a reduction of 71% compared to the treatment scenario and of 66% compared with the conventional scenario. This is because the improved efficiency of the GPM system.

The impact results for FE, on the other hand, were significantly increased with respect to both the treatment and conventional scenarios due to the higher amounts of fertilizer required per surface area to meet the N crop needs. As previously explained, the GPM system reduces N levels, whilst maintaining same P levels in the treated manure. There- fore, the more organic fertilizer is applied, the more P is applied and leached to groundwater reservoirs.

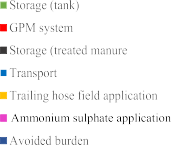
These results indicate that the optimized treatment scenario can lead to an overall better environmental performance compared to the con- ventional scenario, thus the GPM system, subjected to optimum design conditions, can represent a better manure management option for swine manure treatment from an environmental sustainability perspective. Moreover, a global management system with effective nutrient surplus management and closing the N cycle would be desirable from an envi- ronmental perspective, and in particular, in areas with poor water quality or with a higher nutrient imbalance, where treatment is neces- sary [[24]](#_bookmark32).

* 1. *Comparison with other studies*

This section presents a comparison of the results obtained in this study with similar LCA of different technologies for livestock wastewater

**Fig. 5.** Life cycle environmental impacts for the optimized treatment scenario per m3 of treated manure. [The values of some impacts have been scaled to fit. To obtain original values, multiply total values by the scaling factor on the x-axis. For impacts nomenclature see [Fig. 3](#_bookmark8)].



treatment, reported in literature: Corbala-Robles et al. [[24]](#_bookmark32), Lopez-Ridaura et al. [[25]](#_bookmark33), Brockmann et al. [[26]](#_bookmark34) and Hoeve et al. [[27]](#_bookmark35). The comparison will allow validating the results of this study and identifying advantages of the different technologies currently applied. Thus, it will enable stakeholders to make informed decisions when it comes to improving the sustainability of the agricultural sector. These studies are summarized in Table S4 (Supplementary materials). These studies used nitrification-denitrification processes [[24,25,26]](#_bookmark32) and N recovery via stripping to produce ammonium sulfate [[27]](#_bookmark35). Only the studies that assessed waste scenarios for swine manure using similar functional units were considered here for consistency. All studies used an attributional approach, except Hoeve et al. [[27]](#_bookmark35), which followed the consequential LCA approach. Whilst the former approach is funda- mentally different from attributional LCA [[50]](#_bookmark52), the study by Hoeve et al.

[[27]](#_bookmark35) is the only one reported in literature that considered a treatment scenario using stripping to recover N producing ammonium sulfate, similar to the treatment scenario presented here. In addition, the aim of that study and system boundaries are comparable with the present one and the other studies considered here. Therefore, it was decided to include the findings reported by Hoeve et al. [[27]](#_bookmark35) for a general com- parison and any discrepancies should be treated with certain reserve. Hoeve et al. [[27]](#_bookmark35) studied four different treatment scenarios, as described in Table S4, and for the purpose of this comparison, only the treatment scenario “Decanter centrifuge with NH3 stripping” is compared here. In this treatment scenario, once the liquid and solid fractions were sepa- rated by centrifugation, the liquid fraction was treated through a strip- ping process for the recovery of N (as ammonium sulfate), and the



storage, transport and application stages were considered, as well as the displacement of mineral fertilizer shown as system credits.

Comparisons across studies were only possible for impact categories with same units, which in this case included GW, FE, ME and TA. The differences found in the net impact results on each impact category could be related with the use of different emissions factors according to locations, storage systems, emissions considered, etc. [[40]](#_bookmark47).

The results for GW are shown in [Fig. 6](#_bookmark12) and the results for FE, ME and TA can be found in Figs. S1, S2. For the conventional scenario, the estimated GW results in this study agree with the “no treatment scenario” ones reported in the reference studies ([Fig. 6](#_bookmark12)). In all these studies, the main impact for GW was the storage stage over the impact of the field application stage, as a result of storing the manure for long periods of time, as reported previously by Corbala-Robles et al. [[24]](#_bookmark32). Emissions of CH4 and N2O, as well as CO2 and NH3 depend strongly on manure composition and storage conditions. Management and environmental conditions are determinant for the choice of emission factors, and therefore the quantification of the associated impacts of CH4 and N2O emissions can explain the differences between the net impacts reported across these studies [[40,51]](#_bookmark47).

For the treatment scenario, the results of this study are consistent with those obtained by Lopez-Ridaura et al. [[25]](#_bookmark33) and Hoeve et al. [[27]](#_bookmark35), where the main impacts for GW were attributed to storage and to the treatment system. Brockmann et al. [[26]](#_bookmark34) included the storage as a part of the treatment as “homogenization tank”, therefore the majority of the GW impact was found in the treatment stage. In the same line, Corbala-Robles et al. [[24]](#_bookmark32) did not considered emissions in the storage

**Fig. 6.** GW results reported in LCA studies of different swine manure treatment scenarios. [Treatment scenario in all other studies involved a biological treatment with composting.].



phase in the treatment scenario, since the raw manure is stored in a buffer tank and passes to the centrifugation process, where the emissions are assessed in the biological treatment phase. All the treatment sce- narios presented a lower GW impact than the no-treatment scenario, except for Lopez-Ridaura et al. [[25]](#_bookmark33), (4% higher) which could be due to a relative higher energy consumption, and Hoeve et al. [[27]](#_bookmark35), who pre- sent a net impact 3% higher in the treatment scenario. In this case, it was reported that greenhouse gas emissions (GHG) were higher during the stripping phase but they were compensated partially for a higher min- eral fertilizer replacement. From an energetic point of view, different reference studies that use nitrification-denitrification process, reported lower electricity consumption than the GPM treatment, considering centrifugation, aeration and pumping in the treatment process, ranging between 14.5 and 18.7 kWh/m3 of manure [[24,25,26]](#_bookmark32). Nevertheless, the electricity consumption and its impacts can vary depending on many factors included country specific electricity mixes and data availability for the various stages, e.g. inclusion of composting process. It is worth mentioning that, although the electricity consumption could be lower for some stages of the nitrification-denitrification process, this treatment does not recover N, and although the treated manure becomes a less harmful substance for the environment, the N as nutrient is lost. In contrast, Hoeve et al. [[27]](#_bookmark35) reported a total electricity consumption of 73 kW/m3 of manure for the recovering of N via stripping, which is 86% higher than the electricity demand of the GPM system (i.e., 39.2 kW/m3 of manure).

The results of this study for the FE category, are consistent with those

obtained by Hoeve et al. [[27]](#_bookmark35), where the treatment scenario had a lower net impact than the no-treatment scenario. Furthermore, both in the no-treatment scenario and in the treatment scenario, the stage that contributed the most was the field application. Corbala-Robles et al.

[[24]](#_bookmark32) reported a higher impact in the treatment scenario due to the P leaching of compost application on the field; nevertheless, they reported that 89% of this impact was compensated with the mineral fertilizer replacement. Regarding ME, the results estimated in this study for the conventional scenario agreed with Corbala-Robles et al. [[24]](#_bookmark32), Brock- mann et al. [[26]](#_bookmark34) and Hoeve et al. [[27]](#_bookmark35), where the treatment scenario presented a lower impact in all cases (approximately 50%). In the same line than this study, Brockmann et al. [[26]](#_bookmark34) and Hoeve et al. [[27]](#_bookmark35) re- ported that the field application stage was the highest contributor to the ME impact. In contrast, Corbala-Robles et al. [[24]](#_bookmark32) reported a higher contribution in the manure “treatment plant” stage, due to the electricity production mix in Belgium. It was not possible to compare this study’s FE and ME results with the ones reported by Lopez-Ridaura et al. [[25]](#_bookmark33) due to the differences in the methods used, i.e., eutrophication potential reported in kg PO4- eq. per m3 of manure.

For the TA impact category, the results of Corbala-Robles et al. [[24]](#_bookmark32), Brockmann et al. [[26]](#_bookmark34) and Hoeve et al. [[27]](#_bookmark35), showed lower net impacts for the treatment scenario than the conventional scenario, being the storage stage and the application the main contributors for both sce- narios. In contrast, in the present study the net impact of the treatment scenario is higher than the no-treatment scenario and the major con- tributors are the GPM system and the stages of application of bio-based fertilizers on field (trailing hose of treated manure and ammonium sulfate application, due to some NH3 volatilization during the GPM treatment as explained before). Once this hotspot is analysed and the ratio membrane surface per m3 of swine manure is improved, the results agree with the reference studies.

* 1. *Main outcomes, limitations and recommendations*

The main outcomes resulting from this study, limitations of the work and recommendations for further improvement are presented here. This is in accordance to LCA reporting guidelines such as the ISO method- ology [[29,30]](#_bookmark37), and the International Reference Life Cycle Data System Handbook [[39]](#_bookmark46), as well as other relevant sources [[52]](#_bookmark53).

The results for the conventional scenario (see [Fig. 3](#_bookmark8)) indicate that the

raw manure storage stage largely contributes to the GW impacts, whilst the application stage was identified as the main hotspot for PMF, ME, FE, HOF, EOF, and TA.

When looking at the results for the treatment scenario (see [Fig. 4](#_bookmark9)), the GW, ME, HOF and EOF are between 14% and 50% lower in com- parison with the conventional scenario, due to the better manure man- agement practices including the GPM treatment system. The FE impact is similar to that estimated for the conventional scenario, whilst PMF and TA are 16% and 17% higher than the conventional scenario, respectively, due to some NH3 volatilization. Nevertheless, the perfor- mance of these impact categories can be improved through better membrane design as demonstrated in the sensitivity analysis. Similar to the conventional scenario, the manure storage stage has been identified as the main hotspot for GW. Therefore this stage can be regarded as the major source of GHGs emissions in manure management systems.

The sensitivity analysis results indicated that a better environmental performance can be achieved with higher membrane surfaces, as higher TAN removal and recovery efficiencies can be obtained. For example, the GW, ME, PMF, and TA impacts are reduced between 14% and 80% with respect to the treatment scenario, and between 26% and 86% with respect to the conventional scenario. In the case of HOF and EOF, the results were net negative due to the avoided impacts from displacing mineral fertilizers. In contrast, the results for FE increased significantly for the optimized treatment scenario with respect to both the conven- tional and treatment scenario because of the accumulation of P in the organic fertilizer, as the GPM system does not remove P from the manure. Therefore, future efforts should be focused on P recovery technologies to avoid pollution of freshwater streams and the depletion of this non-renewable resource. From this, it is observed that an optimal membrane ratio per volume of manure is a determinant factor to consider when designing this technology.

The findings from this environmental sustainability assessment demonstrated that the GPM technology is a more environmentally sus- tainable option for livestock wastewater treatment, as it significantly reduces NH3 emissions from such activities. Alongside its good technical and economic performance, the GPM technology could lead to new strategic approaches for the treatment of other ammonia-rich waste streams, and be considered as one of the “Best Available Techniques” for wastewater treatment in the agri-food sector. It is hoped that the find- ings from this work will help policy makers and all the stakeholders across the agroindustry, and in the livestock sector in particular, to improve the sustainability of the agricultural chain when it comes to selecting best waste management and nutrient valorization practices.

# Conclusions

This work presented for the first time an LCA of a swine manure treatment system using the novel GPM technology for capturing NH3 from wastewaters, thus minimizing their emissions and recovering N as a nutrient. The assessment considered a total of seven environmental impact categories including GW, PMF, and ME, as common emissions from the agricultural sector such as NH3, NOx, NO - are known con- tributors to these categories. The treatment scenario was compared to a conventional scenario for reference, where no treatment of the swine manure is carried out.

3

The treatment scenario presented a better environmental perfor- mance with respect to the conventional scenario for most impact cate- gories. For instance, the results for the GW is 14% lower compared to the conventional scenario, due to the better manure management practices including the GPM treatment system. For PMF and TA, the results are 16% and 17% higher, respectively, due to some NH3 volatilization. This issue has been addressed via a sensitivity analysis looking at an optimum membrane surface per volume of swine manure ratio.

The results indicated that further reductions are possible for most impact categories thus improving its environmental sustainability per- formance. For instance, notable reductions were observed for GW

(26%), ME (86%), PMF (74%) and TA (66%) compared to the conven- tional scenario. This is because higher TAN removal and recovery effi- ciencies can be achieved with higher membrane surfaces. In contrast, the results for FE increased significantly for the optimized treatment scenario with respect to both the conventional and treatment scenario because of the accumulation of P in the organic fertilizer, as the GPM system does not remove P from the manure.

Overall, the GPM system represents a more environmentally sus- tainable option compared to the conventional scenario as it is capable of significantly reducing NH3 emissions, and enabling the recovery and redistribution of nutrients back to the soil in a controlled way, whilst reducing most impact categories assessed here.

# References

1. [European Commission, Directorate-General for the Environment, Resource](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref1) [efficiency in practice – Closing Mineral Cycle. Final Report, Publications Office of](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref1) [the European Union, 2016](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref1).
2. EUROSTAT. 2017. Archive: Agri-environmental indicator - ammonia emissions. accessed on 09/2021.

1. [A. Buckwell, E. Nadeu, Nutrient Recovery and Reuse (NRR) in European](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref2) [agriculture. A review of the issues, opportunities, and actions, RISE Foundation,](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref2) [Brussels, 2016](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref2).
2. K. Chojnacka, K. Moustakas, A. Witek-Krowiak, Bio-based fertilizers: A practical approach towards circular economy, Bioresour. Technol. 295 (2020), 122223, <https://doi.org/10.1016/j.biortech.2019.122223>.
3. European Commission, 2019. Communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions. The European Green Deal. COM/2019/640 final Available here [〈https://eur-lex.europa.eu/legal-content](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640)

[/EN/TXT/?uri=CELEX:52019DC0640〉](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640), accessed on 06/2021.

1. [C.H. Burton, J. Beck, P.F. Bloxham, P.J.L. Derikx, J. Martinez, Manure](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref4) [Management. Treatment strategies for sustainable agriculture, Silsoe Research](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref4) [Institute (1997)](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref4).
2. Spanish Royal Decree 306, 2020, February 11. Basic regulations for the management of intensive pig farms, and modifies the basic regulations for the management of extensive pig farms. BOE 38, Agencia Estatal Boletin Oficial del

Estado, Madrid. Available online at: [〈https://www.boe.es/eli/es/rd/2020/02/11/](https://www.boe.es/eli/es/rd/2020/02/11/306) [306〉](https://www.boe.es/eli/es/rd/2020/02/11/306), accessed 06/20.

1. European Commission, 2020a. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. A Farm to Fork Strategy. or a fair, healthy and environmentally-friendly food system. Available here [〈https://eur-lex.europa.eu/le](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0381) [gal-content/EN/TXT/?uri=CELEX%3A52020DC0381〉](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0381); accessed on 06/2021.
2. L. Loyon, Overview of Animal Manure Management for Beef, Pig, and Poultry Farms in France, Front. Sustain. Food Syst. 2 (2018), [https://doi.org/10.3389/](https://doi.org/10.3389/fsufs.2018.00036) [fsufs.2018.00036](https://doi.org/10.3389/fsufs.2018.00036).
3. B. Molinuevo-Salces, B. Rian˜o, M.B. Vanotti, D. Herna´ndez-Gonz´alez, M.C. García- Gonza´lez, Pilot-scale demonstration of membrane-based nitrogen recovery from swine manure, https://doi: Membranes 10 (2020) 270, [https://doi.org/10.3390/](https://doi.org/10.3390/membranes10100270) [membranes10100270](https://doi.org/10.3390/membranes10100270).
4. A. Bonmatí, X. Flotats, Air stripping of ammonia from pig slurry: Characterization and feasibility as a pre-or post-treatment to mesophilic anaerobic digestion, Waste Manag 23 (2003) 261–272, <https://doi.org/10.1016/S0956-053X(02)00144-7>.
5. Z. Milan, E. S´anchez, P. Weiland, C. de Las Pozas, R. Borja, R. Mayari, N. Rovirosa, Ammonia removal from anaerobically treated piggery manure by ion exchange in columns packed with homoionic zeolites, Chem. Eng. J. 66 (1997) 65–71, [https://](https://doi.org/10.1016/S1385-8947(96)03180-4) [doi.org/10.1016/S1385-8947(96)03180-4](https://doi.org/10.1016/S1385-8947(96)03180-4).
6. S. Uludag-Demirer, G.N. Demirer, S. Chen, Ammonia removal from anaerobically digested dairy manure by struvite precipitation, Process Biochem 40 (2005) 3667–3674, <https://doi.org/10.1016/j.procbio.2005.02.028>.
7. M. B. Vanotti, A. A. Szogi, Systems and Methods for Reducing Ammonia Emissions from Liquid Effluents and for Recovering the Ammonia. U.S. Patent 9,005,333 B1. 2015.
8. P.J. Dube, M.B. Vanotti, A.A. Szogi, M.C. Garcia-Gonza´lez, Enhancing recovery of ammonia from swine manure anaerobic digester effluent using gas-permeable membrane technology, Waste Manag 49 (2016) 372–377, [https://doi.org/](https://doi.org/10.1016/j.wasman.2015.12.011) [10.1016/j.wasman.2015.12.011](https://doi.org/10.1016/j.wasman.2015.12.011).
9. A. Beckinghausen, M. Odlare, E. Thorin, S. Schwede, From removal to recovery: an evaluation of nitrogen recovery techniques from wastewater, Appl. Energy. 263 (2020), 114616, <https://doi.org/10.1016/j.apenergy.2020.114616>.
10. S. Munasinghe-Arachchige, N. Nirmalakhandan, Nitrogen-Fertilizer Recovery from the Centrate of Anaerobically Digested Sludge, Environ. Sci. Technol. Lett. 7 (2020) 450–459, <https://doi.org/10.1021/acs.estlett.0c00355>.
11. B. Pandey, L. Chen, Technologies to recover nitrogen from livestock manure - A review, Sci. Total Environ 784 (2021), 147098, [https://doi.org/10.1016/j.](https://doi.org/10.1016/j.scitotenv.2021.147098) [scitotenv.2021.147098](https://doi.org/10.1016/j.scitotenv.2021.147098).
12. M.C. García-Gonza´lez, M.B. Vanotti, A.A. Szogi, Recovery of ammonia from swine manure using gas-permeable membranes: effect of aeration, J. Environ. Manage. 152 (2015) 19–26, <https://doi.org/10.1016/j.jenvman.2015.01.013>.
13. M.C. García-Gonz´alez, M.B. Vanotti, Recovery of ammonia from swine manure

using gas-permeable membranes: effect of waste strength and pH, Waste Manag 38 (2015) 455–461, <https://doi.org/10.1016/j.wasman.2015.01.021>.

1. B. Rian˜o, B. Molinuevo-Salces, M.B. Vanotti, M.C. García-Gonz´alez, Application of Gas-Permeable Membranes For-Semi- Continuous Ammonia Recovery from Swine Manure, Environments 6 (2019) 32–45, [https://doi.org/10.3390/](https://doi.org/10.3390/environments6030032) [environments6030032](https://doi.org/10.3390/environments6030032).
2. European Commission, 2020b. Study on Future of EU livestock: how to contribute to a sustainable agricultural sector? Final report. Available here [〈https://ec.europa.](https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/cmef/farmers-and-farming/future-eu-livestock-how-contribute-sustainable-agricultural-sector_en) [eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/cmef/fa](https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/cmef/farmers-and-farming/future-eu-livestock-how-contribute-sustainable-agricultural-sector_en) [rmers-and-farming/future-eu-livestock-how-contribute-sustainable-agricultural-](https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/cmef/farmers-and-farming/future-eu-livestock-how-contribute-sustainable-agricultural-sector_en) [sector\_en〉](https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/cmef/farmers-and-farming/future-eu-livestock-how-contribute-sustainable-agricultural-sector_en); accessed on 06/2021.
3. E. Cherubini, G.M. Zanghelini, R.A.F. Alvarenga, D. Franco, S.R. Soares, Life cycle assessment of swine production in Brazil: a comparison of four manure management systems, J. Clean. Prod. 87 (2015) 68–77, [https://doi.org/10.1016/j.](https://doi.org/10.1016/j.jclepro.2014.10.035) [jclepro.2014.10.035](https://doi.org/10.1016/j.jclepro.2014.10.035).
4. L. Corbala-Robles, W.N.D. Sastafiana, V. Van linden, E.I.P. Volcke, T. Schaubroeck, Life cycle assessment of biological pig manure treatment versus direct land application- a trade-off story, Resour. Conserv. Recyl 131 (2018) 86–98, [https://](https://doi.org/10.1016/j.resconrec.2017.12.010) [doi.org/10.1016/j.resconrec.2017.12.010](https://doi.org/10.1016/j.resconrec.2017.12.010).
5. S. Lo´pez-Ridaura, H. van der Werf, J.M. Paillat, B. Le Bris, Environmental evaluation of transfer and treatment of excess pig slurry by life cycle assessment,

J. Environ. Manage. 90 (2009) 1296–1304, [https://doi.org/10.1016/j.](https://doi.org/10.1016/j.jenvman.2008.07.008) [jenvman.2008.07.008](https://doi.org/10.1016/j.jenvman.2008.07.008).

1. D. Brockmann, M. Hanhoun, O. N´egri, A. H´elias, Environmental assessment of

nutrient recycling from biological pig slurry treatment – Impact of fertilizer substitution and field emissions, Bioresour. Technol. 163 (2014) 270–279, [https://](https://doi.org/10.1016/j.biortech.2014.04.032) [doi.org/10.1016/j.biortech.2014.04.032](https://doi.org/10.1016/j.biortech.2014.04.032).

1. M. ten Hoeve, N.J. Hutchings, G.M. Peters, M. Svanstro¨m, L.S. Jensen, S. Bruun, Life cycle assessment of pig slurry treatment technologies for nutrient redistribution in Denmark, J. Environ, Manage. 132 (2014) 60–70, [https://doi.org/](https://doi.org/10.1016/j.jenvman.2013.10.023) [10.1016/j.jenvman.2013.10.023](https://doi.org/10.1016/j.jenvman.2013.10.023).
2. N. Gontard, U. Sonesson, M. Birkved, M. Majone, D. Bolzonella, A. Celli,

H. Angellier-Coussy, G.-W. Jang, A. Verniquet, J. Jan Broeze, B. Burkhard Schaer,

A.P. Batista, A. Sebok, A research challenge vision regarding management of agricultural waste in a circular bio-based economy, Crit. Rev. Environ. Sci. Technol. 48 (6) (2018) 614–654, [https://doi.org/10.1080/](https://doi.org/10.1080/10643389.2018.1471957)

[10643389.2018.1471957](https://doi.org/10.1080/10643389.2018.1471957).

1. [ISO 14040, Environmental management — Life cycle assessment — Principles and](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref23) [framework (2006)](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref23).
2. [ISO 14044, Environmental management — Life cycle assessment — Requirements](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref24) [and guidelines (2006)](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref24).

1. [M. Margni, T. Gloria, J. Bare, J. Sepp¨ala¨, B. Steen, J. Struijs, L. Toffoletto, O. Jolliet,](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref25) [Guidance on how to move from current practice to recommended practice in Life](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref25) [Cycle Impact Assessment, UNEP-SETAC Life Cycle Initiative (2008)](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref25).

1. [M. Brander, R. Tipper, C. Hutchison, G. Davis, Consequential and Attributional](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref26) [Approaches to LCA: A Guide to Policy Makers with Specific Reference to](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref26) [Greenhouse Gas LCA of Biofuels, in: Technical Paper, 2, Ecometrica Press, 2008](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref26).
2. GreenDelta, 2016. OpenLCA version 1.10. [〈https://www.openlca.org/greendelta/](https://www.openlca.org/greendelta/)

[〉](https://www.openlca.org/greendelta/), accessed 01/20.

1. K.L. Lam, L. Zlatanovic, J.P. van der Hoek, Life cycle assessment of nutrient recycling from wastewater: a critical review, Water Res 173 (2020), 115519, <https://doi.org/10.1016/j.watres.2020.115519>.
2. Ecoinvent Association, ETH Domain and by Agroscop (2004) version 1.1,

[〈https://www.ecoinvent.org/〉](https://www.ecoinvent.org/).

1. ADEME, AGRIBALYSE® program, Agency of Ecological Transition of the French Republic, 2020. Available here, [〈https://www.ademe.fr/en/agribalyse-program〉](https://www.ademe.fr/en/agribalyse-program). accessed on 06/2019.
2. European Commission, Joint Research Centre (JRC), European Life Cycle Database (ELCD) (2015). Version 3.2 from 2015, [〈https://nexus.openlca.org/databa](https://nexus.openlca.org/database/ELCD) [se/ELCD〉](https://nexus.openlca.org/database/ELCD).
3. European Commission, Environmental Footprint Database, European Platform on Life Cycle Assessment (2018) version 2.0, [〈https://eplca.jrc.ec.europa.eu//Environ](https://eplca.jrc.ec.europa.eu//EnvironmentalFootprint.html) [mentalFootprint.html〉](https://eplca.jrc.ec.europa.eu//EnvironmentalFootprint.html).
4. European Commission - Joint Research Centre -Institute for Environment and Sustainability., 2010. International Reference Life Cycle Data System (ILCD) Handbook -General guide for Life Cycle Assessment -Detailed guidance. Luxembourg. Publications Office of the European Union.
5. IPCC, 2019. Refinement to the 2006 ipcc guidelines for national greenhouse gas inventories. Prepared by the Task Force on National Greenhouse Gas Inventories (TFI) in accordance with the decision taken at the 44th Session of IPCC in Bangkok, Thailand, in October 2016. Available from: [〈www.ipcc.ch/site/assets/uploads/201](http://www.ipcc.ch/site/assets/uploads/2019/12/19R_V0_01_Overview.pdf) [9/12/19R\_V0\_01\_Overview.pdf〉](http://www.ipcc.ch/site/assets/uploads/2019/12/19R_V0_01_Overview.pdf).
6. J.W.D. Vries, C.M. Groenestein, J.J. Schro¨der, W.B. Hoogmoed, W. Sukkel, P.W.G.

G. Koerkamp, I.J.M.D. Boer, Integrated manure management to reduce environmental impact: II. Environmental impact assessment of strategies, Agric. Syst. 138 (2015) 88–99, <https://doi.org/10.1016/j.agsy.2015.05.006>.

1. [REE (Red El´ectrica de Espan˜a), El Sistema el´ectrico espan˜ol (2018) 43](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref33).

1. [M. Sa´nchez-Bascones, Determinacio´n analítica de par´ametros de fertilidad y su](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref34) [interpretacio´n (in Spanish), Universidad de Valladolid, 1998](http://refhub.elsevier.com/S2213-3437(22)00119-1/sbref34).
2. E. Cadena, F. Adani, X. Font, A. Artola, Including an Odor Impact Potential in Life Cycle Assessment of waste treatment plants, Int. J. Environ. Sci. Technol. 15 (2018) 2193–2202, <https://doi.org/10.1007/s13762-017-1613-7>.
3. M. Marchand, L. Aissani, P. Mallard, F. Be´line, J.-P. R´everet, Odour and Life Cycle Assessment (LCA) in Waste Management: A Local Assessment Proposal, Waste Biomass Valor 4 (2013) 607–617, <https://doi.org/10.1007/s12649-012-9173-z>.
4. G.M. Peters, K.R. Murphy, A.P.S. Adamsen, S. Bruun, M. Svanstro¨m, M. ten Hoeve, Improving odour assessment in LCA—the odour footprint, Int J Life Cycle Assess 19 (2014) 1891–1900, <https://doi.org/10.1007/s11367-014-0782-6>.
5. M. Goedkoop, R. Heijungs, M. Huijbregts, A. Schryver, J. Struijs, R. Zelm, ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Ministry of Housing, Spatial Planning and Environment of Netherlands. Report I, 2013.
6. M.A.J. Huijbregts, Z.J.N. Steinmann, P.M.F. Elshout, P.M.F. Elshout, G. Stam,

F. Verones, M. Vieira, M. Zijp, A. Hollander, R. Van Zelm, ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level, Int J Life Cycle Assess 22 (2017) 138–147, [https://doi.org/10.1007/s11367-016-](https://doi.org/10.1007/s11367-016-1246-y) [1246-y](https://doi.org/10.1007/s11367-016-1246-y).

1. T. Ekvall, Attributional and consequential life cycle assessment. Sustain. Assess. 21st Century, IntechOpen (2020) 116–124, [https://doi.org/10.5772/](https://doi.org/10.5772/intechopen.89202) [intechopen.89202](https://doi.org/10.5772/intechopen.89202). Available at, [〈https://www.intechopen.com/books/sustainabi](https://www.intechopen.com/books/sustainability-assessment-at-the-21st-century/attributional-and-consequential-life-cycle-assessment) [lity-assessment-at-the-21st-century/attributional-and-consequential-life-cycle](https://www.intechopen.com/books/sustainability-assessment-at-the-21st-century/attributional-and-consequential-life-cycle-assessment)

[-assessment〉](https://www.intechopen.com/books/sustainability-assessment-at-the-21st-century/attributional-and-consequential-life-cycle-assessment).

1. D. Chadwick, S. Sommer, R. Thorman, D. Fangueiro, L. Cardenas, B. Amon,

T. Misselbrook, Manure management: Implications for greenhouse gas emissions, Anim. Feed Sci. Technol. 166 – 167 (2011) 514–531, [https://doi.org/10.1016/j.](https://doi.org/10.1016/j.anifeedsci.2011.04.036) [anifeedsci.2011.04.036](https://doi.org/10.1016/j.anifeedsci.2011.04.036).

1. L. Zampori, E. Saouter, V. Castellani, E. Schau, J. Cristobal, S. Sala, Guide for interpreting life cycle assessment result; EUR 28266, 2016. [https://doi.org/10.27](https://doi.org/10.2788/171315) [88/171315](https://doi.org/10.2788/171315).