COW2NUTRIENT: an environmental GIS-based decision support tool for the assessment of nutrient recovery systems in livestock facilities

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Abstract

Nutrient pollution of waterbodies is one of the major worldwide water quality problems. Excessive use and discharges of nutrients, mainly phosphorus, can lead to eutrophication and algal blooms in freshwater bodies. As a consequence, environmental problems associated with hypoxia arise due to the decomposition of the excessive organic matter, as well as public health issues related to the release of toxins and scarcity of fresh water. A promising option to address this problem is to recover phosphorus released by human activities prior to being discharged to the environment. Driven by the development of a circular economy approach capable of recovering, redistributing, and reintegrating phosphorus into the production cycle, the COW2NUTRIENT (Cattle Organic Waste to NUTRIent and ENergy Technologies) decision support tool is developed to aid in the evaluation and selection of the most suitable nutrient recovery technology for livestock facilities. Through a multi-criteria decision analysis (MCDA) framework, based on environmental geographic information and techno-economic models, the proposed tool is able to provide a customized solution for individual livestock facilities by evaluating different state-of-the-art nutrient recovery technologies together with power and biofuels generation as an additional source of revenue. Two case studies show the tool application for estimating the necessary investment, technology, and nutrient recovery performance at a facility and regional scale. Therefore, this tool has the potential to be a key component of coordinated management efforts for developing nutrient pollution, and ecosystem integrated responses at regional spatial resolution.

Keywords: Organic Waste, Waste to Energy, Nutrient Pollution, Livestock, Decision Support Tool.

1 Introduction

Phosphorus is a source of concern for modern societies. On the one hand, nutrient pollution of waterbodies is one of the major water quality problems worldwide, resulting in environmental issues as a consequence of the eutrophication of waterbodies, and the occurrence of cyanobacteria and harmful algal blooms (HABs). Surveys reveal that eutrophication is a global problem, reporting that 54% of lakes in Asia, 53% in Europe, 48% in North America, 41% in South America, and 28% in Africa are in eutrophic condition (Ansari, 2010). In addition to eutrophication, hypoxia of aquatic ecosystems is associated with the aerobic degradation of the algal biomass by bacteria, shifting the distribution of aquatic species and releasing toxins in drinking water sources (Sampat et al., 2018). Although eutrophication is affected by several factors, such as temperature and the self-purification capacity of waterbodies, the primary limiting factor for eutrophication is often the phosphate concentration (Werner, 2009). Aside from disturbing aquatic ecosystems, eutrophication also contributes to climate change, emitting large amounts of strong greenhouse gases as a consequence of the biomass degradation, such as CH_4 and N_2O (Beaulieu et al., 2019).

On the other hand, phosphorus is an essential nutrient for living organisms, and a key element for maintaining agricultural productivity. However, phosphorus is a resource very sensitive to depletion, since extractable deposits of phosphorus rock are limited and there is no known substitute or synthetic replacement. Projections estimate limited availability of phosphate over the next century (Cordell et al., 2009). Therefore, in addition to the environmental perspective, the search for phosphorus recycling processes is a major driving force for the development of nutrient recovery systems.

The main contributor to human-based phosphorus releases are agricultural activities (Dzombak, 2011), including non-point source releases by over-use of fertilizers in croplands, point source releases originated from the disposal of livestock waste, and legacy nutrients that have accumulated in watersheds due to historical anthropogenic inputs. Focusing on the point source releases generated by the cattle industry, these result from the production of large amounts of livestock organic waste, containing substantial amounts of phosphate and ammonia. Sampat et al. (2017) presented the link between the presence of livestock facilities and higher concentrations of phosphorus in soil, resulting in increased nutrient runoff to waterbodies. While for animals on pasture, organic waste should not be a source of concern if stocking rates are not excessive, for concentrated animal feeding operations (CAFOs) [1] manure should be properly managed due to the high rates and spatial concentration of the organic waste generated. Currently, in CAFOs the manure is collected and stored as a liquid or slurry in waste storage ponds or in tanks; or as a solid in dry stacking or composting facilities. Also, the liquid fraction of manure can be treated in aerobic or anaerobic ponds (United States Department of Agriculture, 2009a). A common practice to recycle the nutrients contained in the organic waste is the land application of the manure. However, since the high-water content of manure makes its transportation to nutrient deficient locations difficult and expensive, it is usually spread in the surroundings of CAFOs, leading to surplus of nutrients in soils and phosphorus runoff to waterbodies (United States Department of Agriculture, 2009a).

The implementation of nutrient recovery technologies in livestock facilities to capture phosphorus from cattle manure is a promising approach to recycle and leverage nutrients more efficiently, mitigating the nutrient pollution of waterbodies. However, the current technologies that can be implemented in CAFOs differ widely in aspects such as phosphorus recovery performance, final products obtained, capital expenses, and operational costs. Under the inspiring

[1] By U.S. regulatory definition, CAFOs are intensive livestock facilities with 1,000 animal units or more (U.S. Environmental Protection Agency (USEPA), 2012b)

principles of the circular economy for the development of environmentally and economically sustainable productive processes, COW2NUTRIENT (Cattle Organic Waste to NUTRIent and ENergy Technologies), a decision support tool for selecting the most suitable nutrient recovery technologies for cattle concentrated animal feeding operations, is presented along these lines. The nutrient management processes evaluated represent the state-of-the-art for nutrient recovery technologies having the necessary technological maturity to be potentially implemented in livestock facilities. Two aspects are evaluated by the proposed tool before the decision support process is carried out. First, it is able to determine the geospatial environmental sensitivity to nutrient pollution caused by legacy and new inputs of nutrients at watershed resolution. Second, the processes assessment is based on techno-economic models, creating a flexible framework able to collect diverse input values which define each livestock facility operation and its economic context. The information retrieved by these two modules is normalized and aggregated, calculating a composite index for scoring and ranking the technologies as a function of the livestock characteristics according with their performance to provide the most effective solution for each evaluated facility.

2 Tool principles

2.1 Operating procedure

The model developed is a decision support tool for nutrient recovery systems assessment and selection in livestock facilities. The targeted end-users are stakeholders seeking to obtain the maximum economic and environmental performance of a nutrient management system installed in a particular livestock facility, but who do not necessarily have the expertise about engineering, economics, and environmental sciences foundations to evaluate all the parameters involved in the decision making process. A flowchart describing the COW2NUTRIENT tool is presented in Fig. 1. The approach considered emphasizes the minimization and simplicity of user data entry to characterize the size of the CAFO and the distribution of the animals regarding their type and age, as well as the geographic location of the facility. The processes assessment of the COW2NUTRIENT tool is based on the techno-economic modeling of the different stages involved in the nutrient recovery process, as well as a geographic information system (GIS) module to evaluate the vulnerability and nutrient pollution conditions due to nutrient legacy of the watershed where the livestock facility evaluated is located, determining the preference of criteria used in the multi-criteria decision analysis (MCDA) module. For the techno-economic evaluation module to be flexible, including changes to government incentives and utility prices, economic parameters can be customized, although predefined values are suggested to guide the users through the data entry stage. The MCDA module compares and ranks the technologies as a function of the geographic location and the characteristics of the facility provided by the user considering technical, economic and environmental factors. Finally, the results for the economic performance, nutrient recovered, and mass balances for all equipment and processes are retrieved, as well as the recommended technology. In addition, interactive maps evaluating phosphorus level in soil, the trophic state of the waterbodies, and the balance between anthropogenic phosphorus releases and uptakes in the contiguous United States are provided to users for informational purposes.

2.2 User interface

A web-based user interface has been designed to make the tool easily accessible and intuitive for users. A detailed description of the tool development can be found in Section 3, while the design and mapping of the tool, as well as the user interface, can be found in Figs. 1. and 2 of the Supplementary Material. Additionally, a web-based tool allows the software to be centralized in a server, making the tool easier to maintain and update.

3 Tool development

The proposed tool is divided in specialized modules performing different tasks: data entry, techno-economic module, environmental geographic information module, and multicriteria-decision analysis module, as shown in Fig. 1. Stages for the anaerobic digestion of organic waste and biogas valorization, producing methane or electricity, can be optionally included, as well as the option to include a manure solid-liquid separation pre-processing stage if the facility is not equipped with this unit.

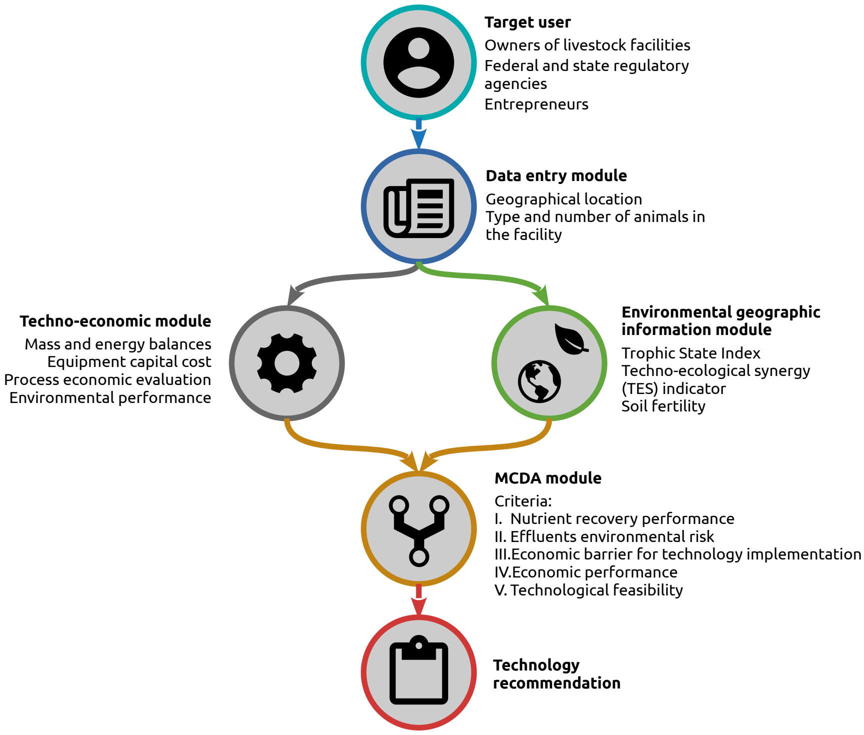


Figure 1: Flow diagram of the decision support tool for nutrient recovery systems.

The output data returned to the user include environmental indicators for the vulnerability to phosphorus pollution of the watershed where the facility is located, mass balance and environmental performance of all processes evaluated, equipment and operation cost, and the recommendation of the most suitable nutrient recovery technology for the evaluated CAFO. All models included in the tool have been developed using Python (van Rossum, 1995).

3.1 Data entry module

To capture the characteristics of each individual facility evaluated, the proposed tool is provided with a data entry interface where users can specify the geographic location (longitude and latitude) and the number of animals in the facility, including beef and dairy cattle, differentiating between adult animals, heifers, and calves, since each type of cattle has different manure generation rates and different manure composition. Data reported by the US Department of Agriculture (USDA) were considered for manure generation ratios (Kellogg et al., 2000) and for the composition of each type of cattle considered (United States Department of Agriculture, 2009a). These values are collected in Table 1 of the Supplementary Material. The optional integration of anaerobic digestion and biogas valorization processes, as well as solid-liquid separation pre-processing stage for the organic waste are also implemented in the data entry module.

For economic performance evaluation purposes, the values of the incentives received for phosphorus recovery (in the form of P credits), and for the generation of bio-based methane or electricity (in form of Renewable Energy Certificate (REC) and Renewable Identification Number (RIN) respectively) are predefined. Renewable Energy Credits is a mechanism implemented in the U.S. which guarantees that energy is generated from renewable sources, providing a system for trading produced renewable electricity. Each produced renewable megawatt-hour generates one REC, that can be sold separately from the electricity commodity itself and can be used to meet regulatory requirements by generators, trades, or end-users. On the other hand, RINs are identification numbers assigned to batches of biofuel, allowing the tracking of its production, purchase, and final usage, which are associated with incentives for the generation bio-fuels. However, the values of these parameters can be customized to adapt the model to different economic scenarios. In addition, potential incentives to partially cover the capital cost of the nutrient recover process are also considered. The predefined value of the different incentives are collected in Table 2 of the Suplemmentary Material.

3.2 Environmental geographic information module

The geographic location of livestock facilities determines the preference (i.e., ranks the importance) of each criterion as a function of three local environmental indicators: the phosphorus saturation of the soils as a result of nutrient legacy (Espinoza et al., 2006), the average Trophic State Index (TSI) of the waterbodies located in each watershed (Carlson, 1977), and the balance between anthropogenic phosphorus releases and uptakes measured using the techno-ecological synergy (TES) metric (Bakshi et al., 2015). Maps showing the values of these parameters for the contiguous U.S. are provided in the Supplementary Material.

3.2.1 Spatial resolution

A watershed is defined as the region draining all the streams and rainfall to a common waterbody, defining the geographic limits for the collection of runoff elements. U.S. watersheds are designated by the U.S. Geological Survey (USGS) through the Hydrologic Unit Code (HUC) system. The HUC system divides the U.S. into regions, subregions, basins, subbasins, watersheds, and subwatersheds. Each hydrologic unit of these six levels is identified hierarchically by a unique numeric code from 2 to 12 digits (i.e., HUC2 to HUC12). The spatial resolution of this study is the contiguous United States at the subbasin level, defined by the HUC system at 8 digits (HUC8) (U.S. Geological Survey, 2013).

3.2.2 Trophic State Index

The Trophic State Index (TSI) is a metric, proposed by Carlson (1977) (Carlson, 1977) and used by the U.S. Environmental Protection Agency (USEPA) to determine the trophic status of waterbodies (U.S. Environmental Protection Agency (USEPA), 2012a). This index can be calculated using three parameters: concentration of chlorophyll-α (chl-α), concentration of total phosphorus, and water turbidity measured through the Secchi depth. Correlations to compute the TSI from these parameters can be found in (Carlson, 1977). The TSI of a waterbody is scored in a range from zero to one hundred, which can be correlated with the oligotrophic, mesotrophic, eutrophic and hypereutrophic classes as shown in Table 1. Among these trophic classes, oligotrophic, mesotrophic denote low and intermediate biomass productivity, while the last two are referred to waterbodies with high biological productivity and frequent algal blooms. To determine the Trophic State Index of lentic waters in the contiguous U.S., combined data for chl-α and total phosphorus concentrations retrieved from the National Lakes Assessments (NLA) carried out by the USEPA in the years 2007 and 2012 (U.S. Environmental Protection Agency, 2012a, 2012b). For watersheds without reported data by the USEPA, no TSI value is assigned to them.

Table 1: Relation between TSI value and trophic class.

TSI	<40	40-50	50-70	>70
Trophic Class	Oligotrophic	Mesotrophic	Eutrophic	Hypereutrophic

3.2.3 Techno-ecological synergy sustainability metric (TES)

The techno-ecological synergy sustainability metric (TES) is an indicator proposed by Bakshi et al. (2015) to evaluate the fraction of net anthropogenic phosphorus, Eq. 1.

$$V_x = \frac{(U_x - E_x)}{E_x} \tag{1}$$

A negative value for TES indicator (V_x) indicates that the releases (E_x) are larger than the uptake capacity of the system evaluated, (U_x), impacting in the ecosystems, while positive values reflects that the releases can be absorbed by the system.

Agricultural releases are a main source of human-based phosphorus releases due to the excessive use of synthetic fertilizers and livestock waste for nutrient supplementation in croplands (Dzombak, 2011). Since this work is limited to the assessment of agricultural phosphorus releases, other possible sources of phosphorus releases are not considered. Agricultural phosphorus releases have been estimated from data reported by the Nutrient Use Geographic Information System (NuGIS) project. Further information about the methodology used for the estimation of human-based phosphorus releases can be found in International Plant Nutrition Institute (IPNI) (2012).

Human-based phosphorus uptakes are carried out by the crops grown in each watershed, as well as the phosphorus retained by wetlands. To estimate the phosphorus uptakes of different crops, considering their different phosphorus requirements and yield rate, data from United States Department of Agriculture (2009b) is used. To determine the crops in each area, the land cover uses are first determined using data from the USEPA EnviroAtlas database for the most recent year available (2011), differentiating between croplands, pasturelands, wetlands, and developed areas (urban areas) (Pickard et al., 2015). To estimate the distribution of crops in croplands, including corn, soybeans, small grains, cotton, rice, vegetables, orchards, greenhouse and other crops (i.e., fruits, sugar crops and oil crops) (United States Department of Agriculture, 2019), data from the 2017 U.S. Census of Agriculture is used. In case of two or more crops were harvested from the same land during the year (double cropping), the area was counted for each crop. Since the data from the 2017 U.S. Census of Agriculture are published at HUC6 resolution, they have been reconciled to HUC8 level by the fraction of occupied area by each HUC8 watershed in the corresponding HUC6 watershed. The wetlands phosphorus uptake value assessed is 0.77 gP m^{-2} $year^{-1}$, based on data reported by Kadlec (2016).

3.2.4 Phosphorus saturation of soils

Datasets for samples from the soil A horizon published by the U.S. Geological Survey (USGS) in the "Geochemical and Mineralogical Data for Soils of the Conterminous United States" report was used to evaluate the concentration of total phosphorus along the contiguous U.S. (D. B. Smith et al., 2013). This dataset allows to consider the legacy phosphorous continuously built-up in soils. However, since plants can just uptake an available fraction of total phosphorus, several standardized phosphorus soil tests, such as Olsen, Bray 1 and Mehlich 3 tests, have been developed to estimate P efficiency for crops. To relate total phosphorus and plant available phosphorus, correlations from Allen and Mallarino (2006) are used, Eq. 2, choosing Mehlich 3 (M3P) as P soil measure since is widely used and it is the P soil test least affected by changes in soil pH. Due to the lack of more complete studies, the correlations reported by Allen and Mallarino (2006) for agricultural soils in Iowa are used. Therefore, the M3P estimates calculated for the contiguous U.S. must be considered as an exploratory effort to determine soil quality in an attempt to select the most suitable nutrients management technology according to the geographic environmental indicators.

$$\text{M3P (\%over TP)} = \frac{4.698 \cdot 10^{-1}}{1 + (\text{TotalP (mg/kg)} \cdot 1.336 \cdot 10^{-3})^{-2.148}} \tag{2}$$

The relationship between M3P test value and the quality of soil is shown in Table 2. Soil fertility levels below optimum indicate that nutrient supplementation is necessary to enhance the yield of crops, optimum values indicates that no nutrient supplementation is needed, and excessive soil fertility levels indicate over-saturation of phosphorus in soil, that can reach waterbodies through runoff (Espinoza et al., 2006).

Table 2: Relation between Mehlich 3 phosphorus and soil fertility level (Espinoza et al., 2006).

Soil Fertility Level	M3P soil phosphorus concentration (ppm)
Very Low	<16
Low	16-25
Medium	26-35
Optimum	36-50
Excessive	>50

3.3 Techno-economic module

Manure treatment process involves several stages from organic waste collection to the recovery of nutrients and other by-products such as electricity or biomethane, as represented in Fig 2. The techno-economic module is divided in the following submodules: manure preconditioning, anaerobic digestion of the manure, biogas purification, biogas valorization, and nutrient recovery.

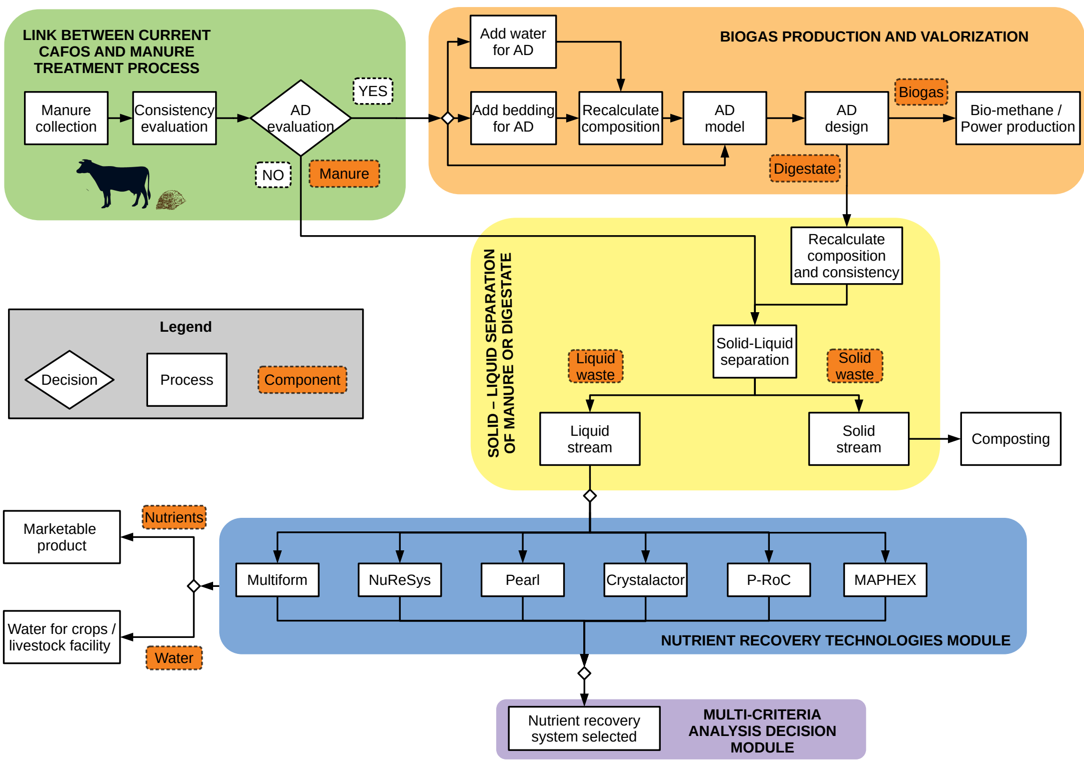


Figure 2: Process flowsheet for manure treatment and nutrients recovery.

3.3.1 Manure preconditioning submodule

It is assumed that livestock facilities already have a manure collection system, and therefore the collection of manure implies no cost for the waste treatment system. If the anaerobic digestion (AD) stage is implemented, a manure preconditioning stage is considered in the process. USEPA determines that the content of total solids in manure should be less than 15%, as shown in Fig. 3 (U.S. Environmental Protection Agency, 2004). Therefore, additional water may be added to reduce the solids content in manure before the anaerobic digestion stage, if necessary.

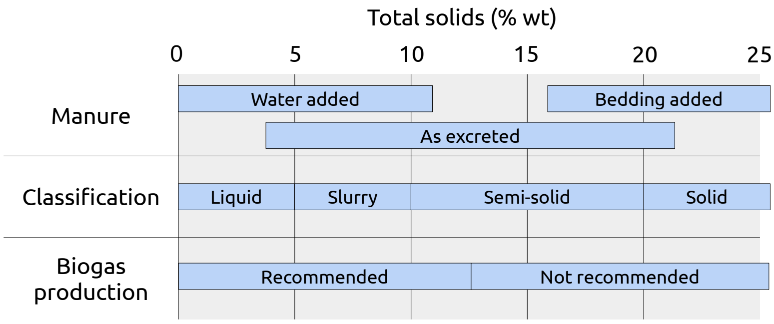


Figure 3: Adequate manure properties for anaerobic digestion. Adapted from U.S. Environmental Protection Agency (2004).

3.3.2 Anaerobic digestion submodule

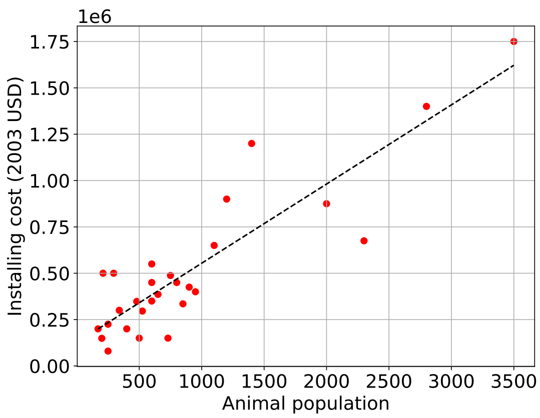
Anaerobic digestion is a microbiological process that breaks down organic matter in the absence of oxygen. It involves four stages, hydrolysis, acidogenesis, acetogenesis, and methanogenesis; producing a mixture of gases mainly composed of methane and carbon dioxide (biogas), and a decomposed organic substrate (digestate). The model of the anaerobic digester is formulated through the mass balances of the species involved in the production of biogas and digestate. A detailed description of the digester modeling can be found in León and Martín (2016). As a result of the anaerobic digestion process, a fraction of organic phosphorus and nitrogen are transformed in their inorganic forms. To evaluate the amount of organic nutrients transformed into inorganic phosphorus and nitrogen, data available in literature was considered, resulting in an increasing of 24% and 16% over the original inorganic ammonia and phosphate respectively, as shown in Table 3 of the Supplementary Material (K. Smith et al., 2007; Martin, 2003; Alburquerque et al., 2012; Sørensen et al., 2011).

Correlations to estimate the capital cost, Eq. 3, and operating and management costs (O&M), Eq. 4, as a function of the animal population of CAFOs were developed using data from the USEPA AgSTAR program (U.S. Environmental Protection Agency, 2003) and the USDA (Beddoes et al., 2007) respectively, shown in Fig. 4. It should be noted that O&M cost does not include the capital cost amortization. Therefore, to estimate the total production cost the annualized equipment cost has been added to O&M Costs, Eq. 5. The plant lifetime assumed is 20 years.

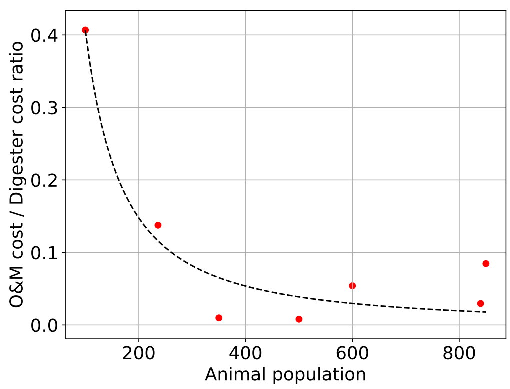
$$\text{Installing cost (USD)} = (427.107 \cdot N_{animals} + 126958.208) \cdot 1.347 \tag{3}$$

$$\frac{\text{O\&M}}{\text{Installing cost}} \text{ ratio} = \frac{15858.710}{(1 + (N_{animals} \cdot 13.917)^{1.461}} \tag{4}$$

$$\text{Operation cost} = \text{O\&M costs} + \frac{\text{Investment cost}}{\text{Plant lifetime}} \tag{5}$$



(a) Cost of anaerobic digestion units as a function of the number of animals (cattle). Data from U.S. Environmental Protection Agency (2003).



(b) O&M costs as a funtion of the number of animals (cattle). Data from Beddoes et al. (2007)

Figure 4: Correlations between anaerobic digestion and capital and O&M costs, and number of cattle in livestock facility.

3.3.3 Biogas purification submodule

Before transforming biogas into marketable products, a purification stage has to be carried out to remove H_2S, H_2O, and NH_3. The removal of H_2S is performed in a bed of ferric oxide through the production of Fe_2S_3 operating at a temperature range of 25-50°C. The bed regeneration is carried out using oxygen to produce elemental sulfur and ferric oxide (Fe_2O_3). Water and ammonia are adsorbed using a pressure swing adsorption system (PSA) with zeolite 5A as adsorbent material, operating at low temperature (25°C) and moderate pressure (4.5 bar). The assumed recovery for NH_3 and H_2O is 100%. For further details about the modeling of the biogas purification stage we refer the reader to previous works (León & Martín, 2016; Martín-Hernández et al., 2018).

3.3.4 Biogas valorization submodule

Two final added value products have been considered, methane and electricity, since they can be obtained through relatively simple processes and there exists developed markets for them.

3.3.4.1 Methane production The process considered for methane production is the removal of CO_2 using a PSA system with a bed of zeolite 5A, since this process was demonstrated as the optimal biogas upgrading process by Martin-Hernandez et al. (2020), where further details about the modeling of the PSA system can be found.

3.3.4.2 Electricity production Electricity is produced from biogas through a gas turbine. A Brayton cycle consisting of double-stage compression system, one for the air stream and one for the biogas stream, is considered. Polytropic compression is assumed, with a polytropic index of 1.4 and an efficiency of 85% (Moran et al., 2010). The adiabatic combustion of methane contained in the biogas is assumed, with a pre-heating of the biogas-air mixture, considering the combustion chamber as an adiabatic furnace. An air excess of 20% with respect to the stoichiometric needs, and 100% conversion of the reaction are assumed. Further details for the modeling of the Brayton cycle for electricity production can be found in Martín-Hernández et al. (2018).

3.3.5 Solid-liquid separation submodule

Nutrients contained in organic waste (manure or digestate, depending on whether AD is carried out or not) are present in both organic and inorganic forms. Organic nutrients are chemically bonded to carbon, and they have to be converted into their inorganic forms through a mineralization process to be available for the vegetation to grow. Organic nutrients are mainly contained in the solid phase of organic waste. Inorganic nutrients are water soluble, and they are mostly present in the liquid phase, or bounded to soluble minerals. They are immediately available to plants, including algae involved in the occurrence of algal blooms. To recover the inorganic fraction of nutrients, a solid-liquid separation stage is implemented, keeping the inorganic nutrients in the liquid stage, which will be further processed, and the organic nutrients in the solid phased, which can be composted to mineralize nitrogen and phosphorus and be further used as fertilizers.

Based on the evaluation reported by Møller et al. (2000), a screw press is the technology selected to carry out the solid-liquid separation stage since it is the most cost efficient liquid-solid equipment. The experimental results reported in this study are used to determine the partition coefficients for the different elements, as shown in Table 3.

Table 3: Partition coefficients for solid-liquid manure separation using a screw press unit (Møller et al., 2000)

Element	Solid fraction	Liquid fraction
Total mass	0.08	0.92
Dry matter	0.31	0.69
Org. N	0.09	0.91
Org. P	0.22	0.78

To determine the commercial sizes and number of units necessary as a function of the flow to be treated, data from commercial manufacturers is considered (PWTech Process Wastewater Technologies LLC., 2018). The feasible configurations in terms of screw press diameter and number of units as a function of the waste flow treated are shown in Table 4 of the Supplementary Material. Data reported by Matches (2014) for this type of equipment is used to relate the unit diameter and cost, while the operating costs are calculated assuming power consumption reported by the manufacturer for each model, as shown in Fig. 3 and Table 5 of the Supplementary Material.

Assuming the discretization of units due to the commercial sizes available, the investment and operating costs for the screw press equipment are presented in Fig 4 of the Supplementary Material.

3.3.6 Nutrient recovery submodule

The technologies to recover inorganic phosphorus can be classified in three categories: struvite-based phosphorus recovery, calcium precipitates-based phosphorus recovery, and physical separation systems. Table 4 shows the classification and characteristics of the technologies evaluated. Regarding struvite-based systems, the formation of struvite has been widely described in literature, mainly focused on phosphorus recovery from wastewater (Rahaman et al., 2014; Battistoni et al., 2001). Experimental data available to evaluate the efficiency and feasibility of P recovery through struvite formation are usually developed for municipal wastewater. However, cattle organic waste shows some characteristics that hinder struvite formation, including high ionic strength, which reduces the effective concentration of ions; and the presence of calcium ions competing for phosphate ions (Yan & Shih, 2016), which inhibits a selective recovery by nutrient precipitation techniques. The high variability in the manure composition, as a function of the geographic area, the animal feed, etc., represents an additional challenge for nutrient recovery (Tao et al., 2016). Specific correlations for livestock waste to estimate the molar fraction of PO_4^{3-} and Ca^{2+} recovered as struvite as a function of the amount of calcium contained in the waste were developed in a previous work (Martín-Hernández et al., 2020), Eqs. 6 to 8, where $x_{Ca^{2+}:PO_4^{3-}}$ is referred to the Ca^{2+}/PO_4^{3-} molar ratio, $x_{struvite(PO_4^{3-})}$ is the fraction of phosphorus as phosphate recovered as struvite, and $x_{hydroxyapatite(Ca^{2+})}$ and $x_{CaCO_3(Ca^{2+})}$ are the fraction of calcium recovered as hydroxyapatite and calcium carbonate respectively. All technologies considered are at or near commercial stage. The description of the processes and the correlations used to estimate their equipment and operating costs are collected in the Supplementary Material.

Table 4: Description of nutrient recovery technologies evaluated by the decision support tool.

Technology	Company	Technology type	Technology readiness level	Phosphorus recovery efficiency (%)
Multiform	Multiform Harvest	Struvite-based	9	Eq. 6
Crystalactor	Royal Haskoning DHV	Struvite-based	9	Eq. 6
NuReSys	Nutrient Recovery Systems	Struvite-based	9	Eq. 6
Pearl	Ostara	Struvite-based	9	Eq. 6
P-RoC	Karlsruhe Institute of Technology	Calcium precipitates-based	6	60
MAPHEX	University of Pennsylvania and USDA	Modular phases separation system	7	90

$$x_{struvite\left(PO_4^{3-}\right)} = \frac{0.798}{1 + \left(x_{Ca^{2+}:PO_4^{3-}} \cdot 0.576\right)^{2.113}} \tag{6}$$

$$x_{hydroxyapatite(Ca^{2+})} = -4.321 \cdot 10^{-2} \cdot x^2_{Ca^{2+}:PO_4^{3-}} + 0.313 \cdot x_{Ca^{2+}:PO_4^{3-}} - 3.619 \cdot 10^{-2} \tag{7}$$

$$x_{CaCO_3(Ca^{2+})} = \frac{1.020}{1 + \left(x_{Ca^{2+}:PO_4^{3-}} \cdot 0.410\right)^{1.029}} \tag{8}$$

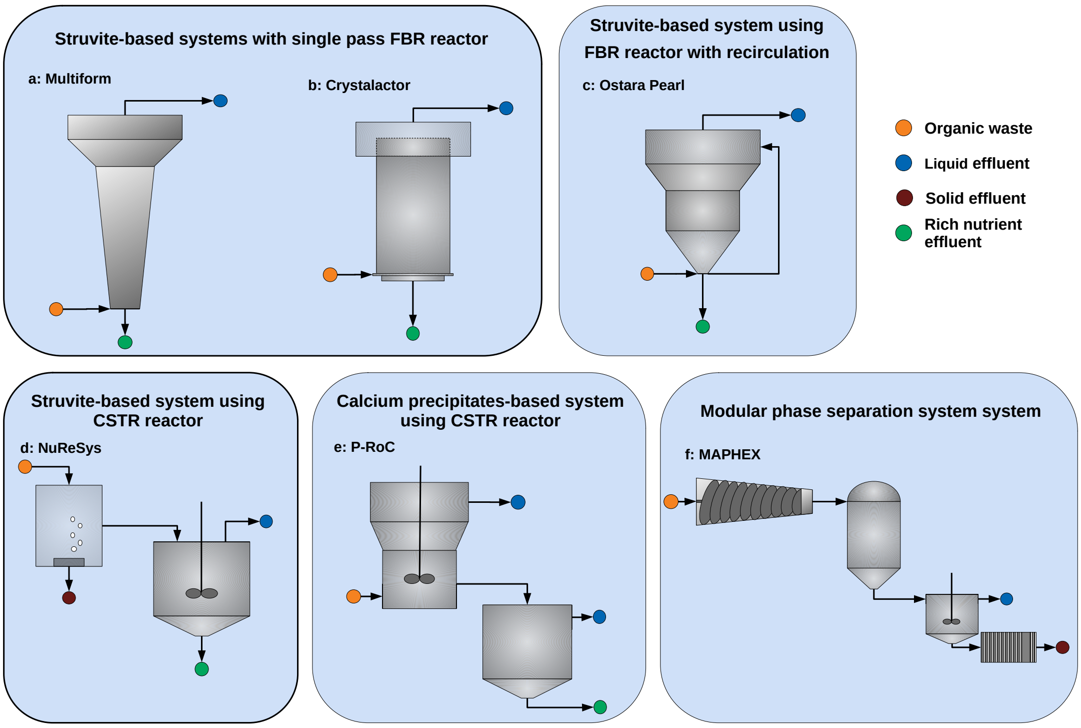


Figure 5: Flowsheets of the nutrient recovery systems considered in the proposed tool. a: Multiform, b: Crystalactor, c:Ostara Pearl, d: Nuresys, e:P-RoC, f: MAPHEX.

3.4 Multi-criteria decision module

The determination of the most suitable nutrient recovery process is not a trivial procedure since multiple criteria play a critical role in the decision-making stage. Therefore, a multi-criteria decision assessment (MCDA) module was developed to address the nutrient recovery technology recommendation stage. Five criteria are considered for the assessment of technologies: overall nutrient performance measuring the fraction of phosphorus recovered, potential environmental threat for the local ecosystem through the eutrophication potential of the effluents of the manure treatment process, economic barrier for the implementation of the process in terms of capital cost, overall economic performance through the net present value (NPV), and technology feasibility using the technology readiness level (TRL) index. These five criteria are weighted according to their importance and combined in a composite index that characterizes each nutrient recovery system in order to compare the different technologies. Indices are an intuitive approach for the stakeholders since they allow summarizing the information of the different indicators considered in one parameter and rank the technologies according to their performance, identifying the best process with respect to the others (Gasser et al., 2020).

TRL index is set as the criteria with highest preference since the aim of the tool is to provide phosphorus recovery processes feasible to be installed and operated in livestock facilities. The prioritization of environmental and economic criteria is carried out based on the environmental information the location of the CAFO evaluated. If there is immediate environmental risk by nutrient pollution (high values for TSI or soil fertility), the environmental performance has preference over economic performance. If there is environmental risk in the long term due to the unbalance between antrophogenic phosphorus releases and uptakes (negative value of TES indicator), or there is no environmental risk, the economic performance has preference over the environmental performance. If there is no data for any criterion in the studied region, this criterion is exempt from the evaluation procedure. Table 5 shows in detail the criteria preference in function of environmental geographic indicators for nutrient pollution. Optionally, users can disable the criteria prioritization based on environmental geographic information and set customized weights for the criteria to adapt the tool to different decision-making scenarios.

The construction of a composite index is composed of three steps: criteria normalization, weighting, and aggregation. Since each criteria has a different range of potential values, these have to be normalized to a common scale to allow each criteria to be compared with the others. The normalized criteria are weighted to set the relative importance of each criteria with respect to the others. The aggregation stage merges the weighted criteria, resulting in the composite index. However, the value of a composite index can be biased by the methodology used to construct the index. To address this issue, different normalization and aggregation techniques are evaluated in order to systematically assess the stability of the indexes obtained and the robustness of the ranking of nutrient recovery technologies. The use of different normalization methods allows the evaluation of different approaches for the comparison of the environmental indicators. The different aggregation schemes denote different degrees of compensability between indicators, i.e. of a deficit in one criteria can be fully, partially, or not compensated by a surplus in other criteria (Gasser et al., 2020). Among the different normalization techniques available, linear normalization methods have been considered: standardization, min-max, and

Table 5: Criteria preference as a function of the GIS-based environmental indicators for nutrient pollution

Local environmental indicators values	Criteria ranking	Comments
Condition 1: TES > TSI and TES > Soil fertility Condition 2: TES = Saturated	TRL > NPV > Capital cost > TP recovered > Eutrophication potential	Unbalanced phosphorus releases but no immediate threat to soil and water bodies. Prevalence of economic criteria for nutrient recovery system selection.
Condition 1: TSI ≥ TES or TSI ≥ Soil fertility Condition 2: TSI = Eutrophic or Hypereutrophic	TRL > Eutrophication potential > NPV > TP recovered > Capital cost	High Trophic State Index. Inmmediate environmental risk due to potential algal blooms. Prevalence of environmental criteria for nutrient recovery system selection.
Condition 1: Soil fertility ≥ TES and Soil fertility > TSI Condition 2: Soil fertility = Excessive	TRL > TP recovered > NPV > Eutrophication potential > Capital cost	Excessive P in soil. Inmmediate environmental risk due to potential P runoff. Prevalence of environmental criteria for nutrient recovery system selection.
Condition: TES ≠ Saturated and TSI ≠ Eutrophic or Hypereutrophic and Soil fertility ≠ Excessive	TRL > NPV > Capital cost > TP recovered > Eutrophication potential	No environmental risk. Prevalence of economic criteria for nutrient recovery system selection.

TRL: Technology Readiness Level
TSI: Trophic State Index
TES: Techno-Ecological Synergy sustainability metric
NPV: Net Present Value
TP: Total Phosphorus

target methods (OECD and European Commission, 2008). Three aggregation functions are evaluated including full compensation (additive aggregation), and partial compensation schemes (geometric and harmonic aggregation methods). Indexes for all combinations of normalization-aggregation methods are computed.

Since the preference of criteria is known as a function of the GIS-based environmental indicators (see Table 5), but the value of the weights is unknown, a stochastic multicriteria acceptability analysis (SMAA) is used to explore the weights space. To formulate the SMAA, the set of n weights (ω) is defined as a non-negative set whose elements must sum 1, as shown in Eqs. 9 and 10.

$$\omega_j \geq 0 \; \forall \, j \; \in \; n \tag{9}$$

$$\sum_{j=1}^{n} \omega_j = 1 \tag{10}$$

In addition to Eqs. 9 and 10, preference information of the criteria, defined through the ranking of the criteria shown in Table 5, is expressed as a sequence of inequality constraints, Eq. 11.

$$\omega_{j1} \geq \omega_{j2} \geq ... \geq \omega_{jn} \tag{11}$$

Therefore, the feasible weight space, including preference information in the form of a ranking of criteria, is defined by the Eqs. 9, 10, and 11 (Tervonen & Lahdelma, 2007). Fig. 6 shows the feasible weight space for a problem with three criteria. The feasible space of each weight is explored through the Monte Carlo method (Tervonen & Lahdelma, 2007), retrieving a set of weights for all criteria according to the assigned order. The 9 combinations normalization-aggregation methods are evaluated using each set of weights obtained using the Monte-Carlo method, obtaining the composite index of each technology for each combination of normalization-aggregation functions. Finally, multiple composite indexes are analyzed to determine the average index value for each technology, and to obtain the ranking of technologies, as shown in Fig 7. A number of Monte-Carlo simulations of 100 is assumed as a trade-off between computation cost and MCDA model performance.

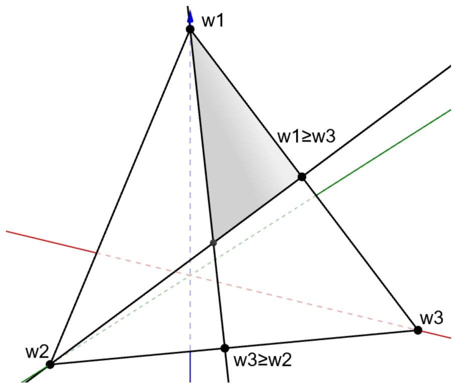


Figure 6: Example of feasible weights space for a three criteria problem considering ranking of criteria. Figure adapted from Tervonen and Lahdelma (2007)

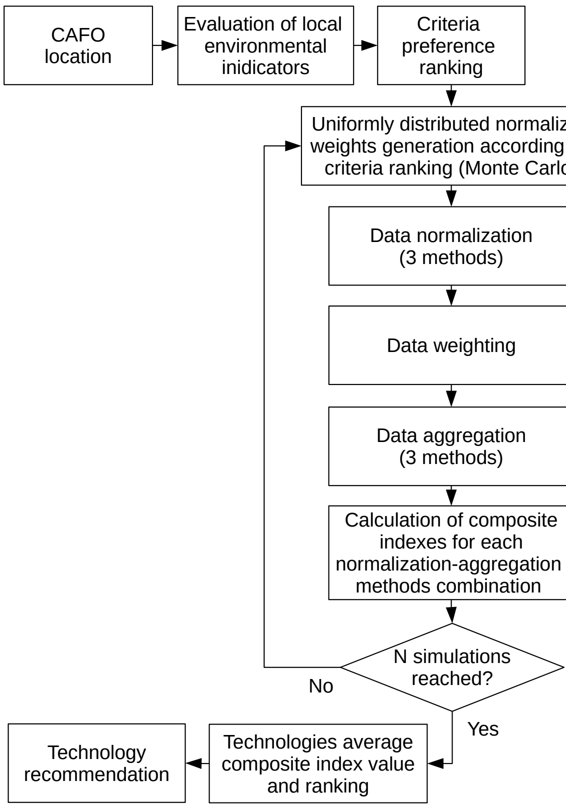


Figure 7: Flowsheet for the MCDA module.

4 Applications

4.1 Evaluation of a typical dairy concentrated animal feeding operation

The use of the COW2NUTRIENT tool is illustrated through the evaluation of a large size dairy CAFO, defined by USEPA as animal concentrated operations with more than 1,000 animals (U.S. Environmental Protection Agency (USEPA), 2012b). To define a representative large dairy CAFO, data from an average dairy producer U.S. state such as Pennsylvania is considered, determining the base case size to compare the facility as the average animal number of the large dairy CAFOs in Pennsylvania, i.e., 2,145 animal units. To evaluate the influence of environmental indicators (i.e., Trophic State Index, TES indicator, and soil fertility level) two locations in the state of Pennsylvania, with low and high vulnerability to nutrients pollution, were selected, as shown in Table 6. The parameters considered for this case study are the addition of a biogas generation stage with electricity production, a value of Renewable Energy Certificates (electricity selling price) of 60 USD per MWh generated, a phosphorus credits value of 22 USD per kilogram of phosphorus recovered, and a discount rate of 7% to calculate the NPV. These values are based on optimal values for the operation of hybrid biogas-nutrient recovery plants reported by Sampat et al. (2018).

Table 6: Geographic locations considered in the dairy CAFO assessment. Values for sentivity to nutrient pollution indicators are expressed between parenthesis

	Longitude	Latitude	Trophic State Index	TES indicator	Soil fertility (M3P ppm)
Scenario 1 (low vulnerability)	-78.4310	39.7910	Oligotrophic (35.6)	Saturated (1.22)	Medium (29.1)
Scenario 2 (high vulnerability)	-76.2269	39.7506	Hypereutrophic (70.30)	Not saturated (-0.57)	Excessive (157)

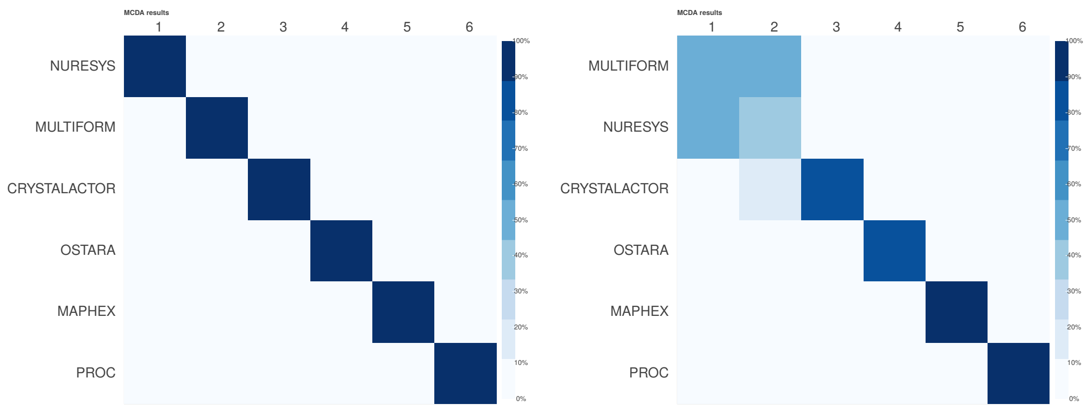
The comparison of the economic results of the cattle waste treatment process for the different nutrient recovery systems evaluated are shown in Table 7. The capital cost ranges between 3.3 and 5.3 million USD for all nutrient recovery processes, while the differences in the operating costs are much more significant. It can be appreciated how the operating costs considering the capital cost amortization for the most technologically mature processes are lower than the processes with a lower technology readiness level. This fact can be attributed to the process optimization carried out prior to their commercial release. This will be the driving factor making the commercial process profitable contrary to the processes still in stages prior to commercial launch. However, when money depreciation is included in the economic evaluation, using NPV as metric, it can be concluded that all of the evaluated nutrient recovery systems fall below the defined rate of return (7%), although the commercial technologies achieve better NPV values than P-RoC and MAPHEX processes.

Table 7: Analysis of the economic performance for diferent nutrient recovery process topologies

	Capital cost (M USD)	Operation cost (w/o amortization) (M USD/year)	Operation cost (w/ amortization) (M USD/year)	Net revenue (M USD/year)	NPV (USD)
Ostara	5.33	0.185	0.413	0.313	-0.209
Multiform	3.94	0.340	0.502	0.224	-0.156
NuReSys	3.65	0.159	0.307	0.403	-0.116
Crystalactor	5.28	0.0776	0.304	0.423	-0.191
P-RoC	4.31	2.32	2.49	-1.96	-0.485
MAPHEX	3.43	2.33	2.47	-1.78	-0.443

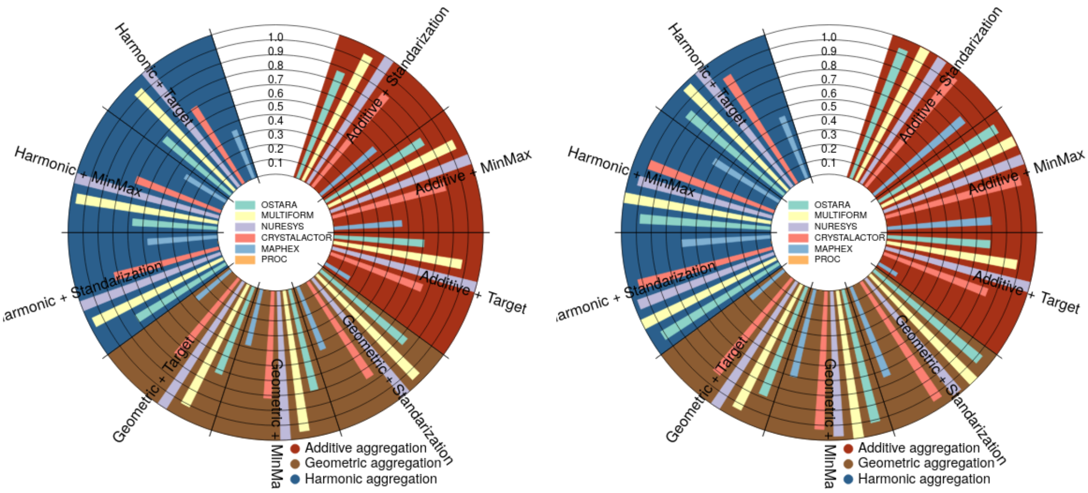
When the results are analyzed using the proposed MCDA module, Figs. 8 and 9, it can be observed how the geographic location of the facility influences the selection of technologies. Fig. 8 shows the ranking of nutrient recovery technologies. The robustness of the results can be observed through the frequency of selecting one technology in a determine ranking position along the SMAA iterations, shown in the figure through the color scale (0%-100%). For the location with low sensitivity to phosphorus pollution, Fig. 8a, where the economic criteria prevails over environmental criteria, a robust solution where NuReSys and Multiform are the two first technologies in the ranking is achieved, showing the best overall performance. However, when the location with high environmental risk is analyzed, Fig. 8b, pursuing a trade-off between environmental criteria and long-term plan operation feasibility, the achieved solution is less robust. Multiform and NuReSys are the technologies on the top of the ranking, but among them there is not a process that clearly prevails over the others since they have the first or the second raking position depending on the normalization-aggregation functions and weight values considered.

These results can be analyzed in more detail when the breakdown of the average scores obtained for each technology using the different normalization-aggregation combinations are evaluated, as shown in Fig. 9. While in scenario 1 it can be observed that the technologies with the highest scores are NuReSys and Multiform, prevailing over the rest of technologies, for scenario 2, four out of six technologies reach a score around 0.9 for most of the normalization-aggregation combinations. Furthermore, the effect of the different levels of compensation between indicators can be observed, where the full compensation level represented by the additive aggregation function retrieve the most homogeneous indexes, while the indexes retrieved by the harmonic function, representing the lower partial compensation level, are more heterogeneous. In both scenarios P-RoC always obtains the lowest score. Therefore, in spite of the raking obtained, as a result of the equity in the scores obtained, the decision about what technology implement for scenario 2 is debatable among the first three technologies retrieved by the ranking.



(a) Scenario 1 (b) Scenario 2

Figure 8: Ranking of nutrient recovery processes. The x-axis represent the ranking position, and the y-axis collects the nutrient recovery systems. The color scale represents the frequency of a technology being selected at a certain position in the ranking.



(a) Scenario 1

(b) Scenario 2

Figure 9: Composite indexes of nutrient recovery processes for each combination of normalization-aggregation methods. The beams represent the normalize composite index value of each nutrient recovery system in a 0 to 1 scale. The different colors of the circle segments denotes the different combinations of normalization-aggregation methods.

4.2 Regional evaluation for the implementation of manure integrated treatment processes

The tool can also be used to aid in the planning of regional scale infrastructures for the treatment of livestock waste. From the information of the location, and number and type of animals of CAFOs in the study area, COW2NUTRIENT estimates the necessary investment, nutrient recovery performance, and the nutrient recovery systems to be installed at each CAFO. Considering the state of Pennsylvania, the information regarding the characteristics and geospatial location of CAFOs is obtained from the Department of Environmental Protection of the Pennsylvania Government (Department of Environmental Protection, Goverment of Pennsylvania, 2019). Assuming the same parameters than in the previous section, the results of the organic waste treatment technologies installed shown in Fig. 10 are summarized in Table 8. Table 9 presents the phosphorus recovery performance and the economic results of carrying out the installation of these processes.

Table 8: Livestock manure treatment technologies selected for the CAFOs of Pennsylvania

	Multiform	NuReSys	Crystalactor	Ostara	MAPHEX	P-RoC
Number of facilities installed	119	11	1	0	0	0

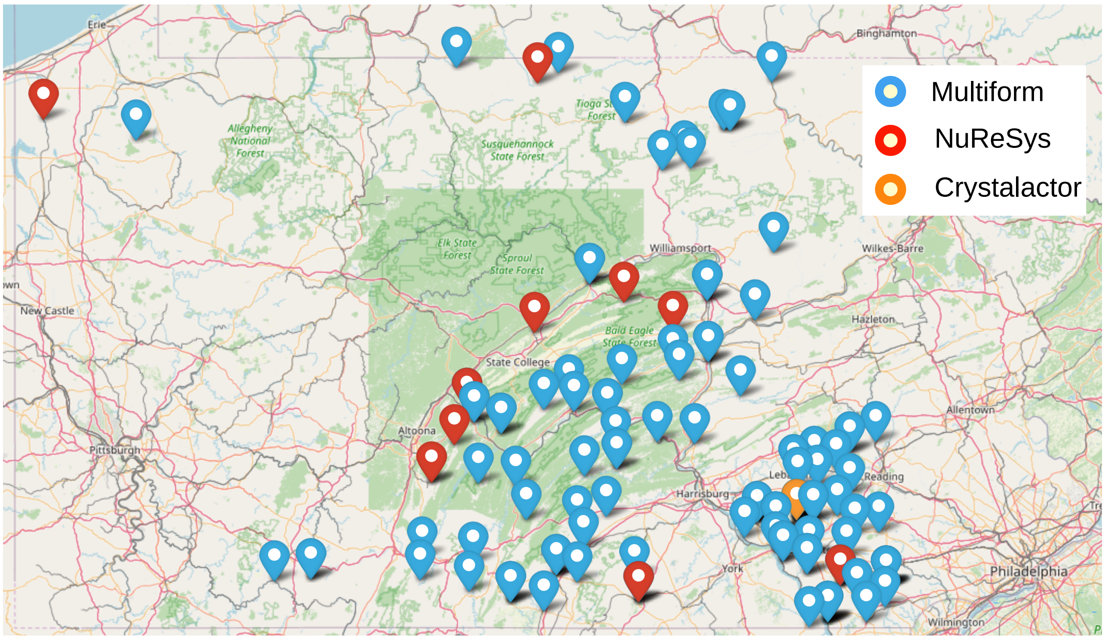


Figure 10: Location of organic manure treatment technologies selected for Pennsylvania

It can be noted that most of the facilities are profitable under the scenario considered. Three technologies are selected for the CAFOs studied, Multiform, NuReSys and Crystalactor. Analyzing the relationship between the sizes of CAFOs and the technologies installed, it can be concluded that the size, and therefore the scale economy, is a key factor for technology recommendation among the cluster of technologies with similar scores. The different available sizes and processing capacity with optimal economic performance of each technology result in that Multiform is the system with the best performance for facilities up to 2000 animal units, NuReSys for CAFOs between 2000 and 7500 animal units, and Crystalactor for facilities with more than 8000 animal units. The selection of manure treatment processes including modular nutrient recovery systems such as MAPHEX, which are specially indicated for small livestock facilities is prevented due to the absence of small CAFOs in Pennsylvania. The large size of the facilities makes that most of the waste treatment facilities installed are profitable, 84 out of 136, recovering the 78% of phosphorus released per year. These findings can aid to optimize the distribution and use of grants available for clean up efforts by minimizing capital costs. The complete results are included in the Supplementary Material.

The reliability of the results obtained depends on the uncertainty in the input data, which increases at smaller scales. A HUC8 spatial resolution has been chosen as a trade-off solution between spatial accuracy and data uncertainty. However, more accurate results can be obtained if reliable data for phosphorus level in soils, fertilizer rates, etc. are available for higher spatial resolution.

Table 9: Phosphorus recovery performance and the economic results of the implementation of livestock waste tratment techologies in Pennsylvania

Manure generated (kg/year)	Phosphorus releases (kg/year)	Phosphorus recovered (kg/year)	Profitable facilities	Capital cost (M USD)	Operation cost (M USD/year)	Net revenue (USD/year)
$2.59 \cdot 10^9$	$2.07 \cdot 10^6$	$1.63 \cdot 10^6$	84	339.75	19.65	12.28

5 Conclusion

Management of anthropogenic nutrients releases is a current challenge that societies must face to mitigate the environmental and public health threats derived from the deterioration of aquatic ecosystems as a consequence of eutrophication and algal blooms. In addition, phosphorus is a non-renewable resource and essential nutrient to support life, and a keystone for the modern agriculture techniques and food security. Forecasts project phosphorus reserves depletion in the next 50 to 100 years (Cordell et al., 2009), and no substitute is known. Therefore, in addition to the environmental perspective, searching for new phosphorus sources is a major driving force for the development of nutrient recovery systems. However, the selection of a nutrient recovery system among the feasible technologies available for its implementation in CAFOs is not trivial; since the decision is affected by different technical, economic, environmental, and geographic factors. In this work, a decision support tool oriented to aid stakeholders as farmers, regulatory agencies, concerned citizens, and investors in the nutrient management system selection stage is presented. Since the target users of the tool may not have technical knowledge, emphasis has been placed on making it intuitive and easy to use. The tool estimates a composite index for each technology as a function of the CAFO size, livestock composition and geographic location, and retrieves a ranking of technologies according with their performance. Also, the tool allows the assessment of the implementation of manure integrated treatment processes for livestock waste at regional scale, estimating the necessary investment, nutrient recovery performance, energy recovery, and the type of technologies to be installed in the study region. Future work is oriented towards the explorariont of the effect of different weighting schemes according to different stakeholder priorities, and the integration of COW2NUTRIENT within a logistics network model (Hu et al., 2019) for the developing of nutrient pollution and ecosystem integrated responses at regional spatial resolution.

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