Supplementary Material: A geospatial environmental and techno-economic framework for sustainable phosphorus management at livestock facilities

Edgar Martín-Hernández[a,b], Mariano Martín[b], and Gerardo J. Ruiz-Mercado[c,*]

[a]ORISE Research Fellow, Center for Environmental Solutions and Emergency Response (CESER), U.S. Environmental Protection Agency, 26 West Martin Luther King Drive, Cincinnati, Ohio 45268, United States

[b]PSEM3 Research Group, Department of Chemical Engineering, University of Salamanca, Plza. Caídos 1-5, 37008 Salamanca, Spain

[c]Center for Environmental Solutions and Emergency Response (CESER), U.S. Environmental Protection Agency, 26 West Martin Luther King Drive, Cincinnati, Ohio 45268, United States

[*]*ruiz-mercado.gerardo@epa.gov*

Contents

1 Environmental geographic information model

1.1 Trophic State Index

Carlson (1977) proposed the Trophic State Index (TSI) as a metric to determine the trophic status of waterbodies. This is used by the U.S. Environmental Protection Agency (US EPA) (United States 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. Only the two first methods has been used in this work since they are less affected to exogenous phenomena (such as atmospheric conditions, or variations in the flow of water streams). Correlations to compute the TSI from these parameters are shown in Eq. 1 and 2 , where Clh denotes the concentration of chlorophyll-α, and TP denotes the concentration of total phosphorus in ${}^{mg}/{}_{m^3}$ (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 1S. Oligotrophic and mesotrophic denote low and intermediate biomass productivities, while eutrophic and hypereutrophic are referred to waterbodies with high biological productivity and frequent algal blooms. Combined data for chl-α and total phosphorus concentrations retrieved from the National Lakes Assessments (NLA) carried out by the US EPA in the years 2007 and 2012 (United States Environmental Protection Agency (USEPA), 2012b, 2012c) is used to determine the Trophic State Index of lentic waters in the contiguous U.S, as shown in Fig. 1S. No TSI values are assigned to the watersheds without reported data.

$$\mathrm{TSI}_{\text{chl-}\alpha} = 10 \cdot \left(6 - \frac{2.04 - 0.68 \cdot \ln\left(Clh\right)}{(2)}\right) \tag{1}$$

$$\mathrm{TSI}_{\mathrm{TP}} = 10 \cdot \left(6 - \frac{\ln\left(\frac{48}{TP}\right)}{(2)}\right) \tag{2}$$

Table 1S: Relation between TSI value and trophic class.

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

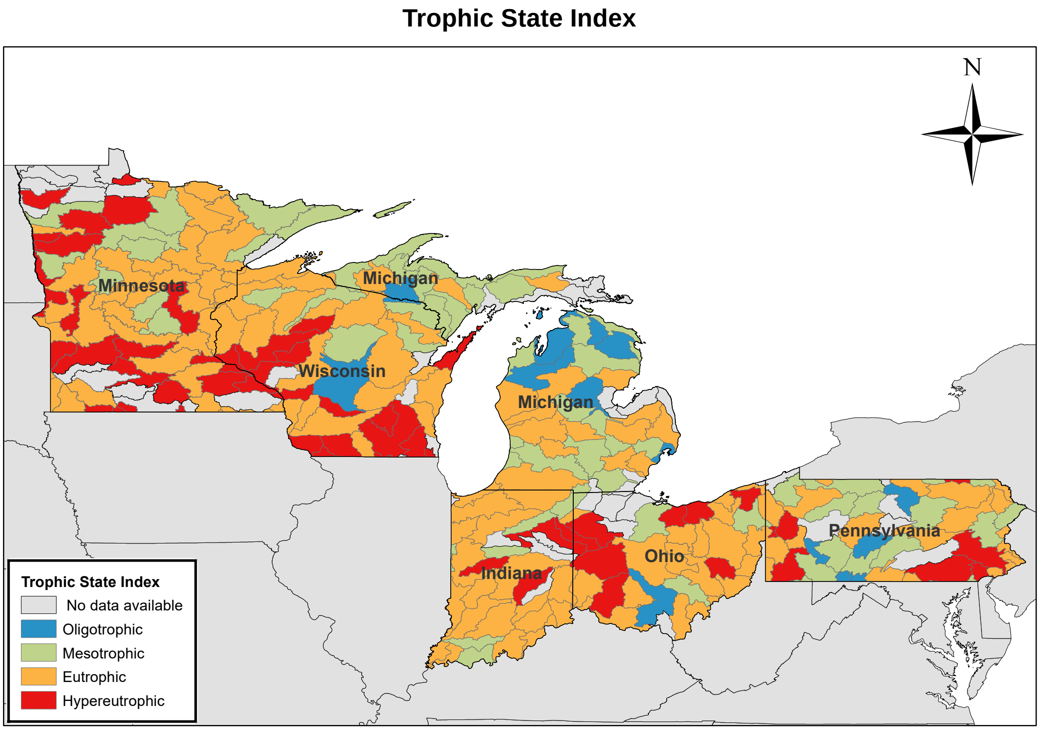


Figure 1S: Trophic State Index in the contiguous US HUC8 watersheds

1.2 Balance of anthropogenic phosphorus releases

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).

The anthropogenic phosphorus uptakes considered are those due to the crops grown in each watershed. In addition, phosphorus retained by wetlands is considered. Data from United States Department of Agriculture (2009) is used to estimate the phosphorus uptakes of different crops, attending to their different phosphorus requirements and yield rates. To determine the crops grown in each watershed, the land cover uses are first determined using data from the US EPA 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).

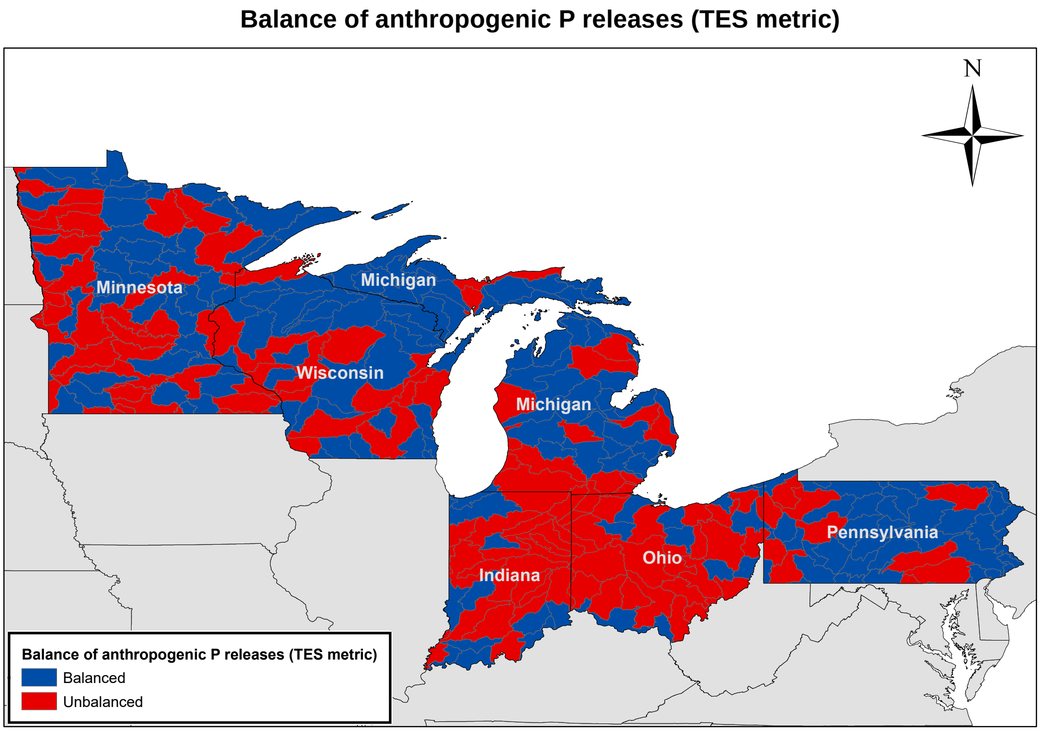


Figure 2S: Balance of anthropogenic phosphorus releases in the contiguous US at a HUC8 spatial resolution

1.3 Phosphorus in soils

Phosphorus concentration in soils is considered to evaluate the legacy phosphorous continuously builds-up in soils. However, only a fraction of phosphorus is available for plants. To measure this phosphorus fraction available for plants, several standardized phosphorus soil tests have been proposed, including Olsen, Bray 1 and Mehlich 3 tests. Among them, Mehlich 3 (M3P) has been selected as a measure of the concentration of P in soils since it is a widely used metric, and it is the P soil test least affected by changes in soil pH. To estimate the fraction of phosphorus available for plants from total phosphorus concentration data, a correlation developed by Allen and Mallarino (2006) has been used, Eq. 3. However, this correlation has been developed for agricultural soils in Iowa. Due to the lack of wider studies in this regard, the M3P estimations calculated for the contiguous U.S. must be considered as an exploratory effort to determine the phosphorus saturation in soils across the the contiguous U.S. in an attempt to select the most suitable nutrients management technology according to the geographic environmental indicators. 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 were used to evaluate the concentration of total phosphorus along the contiguous U.S. (D. B. Smith et al., 2013).

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

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

Table 2S: 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

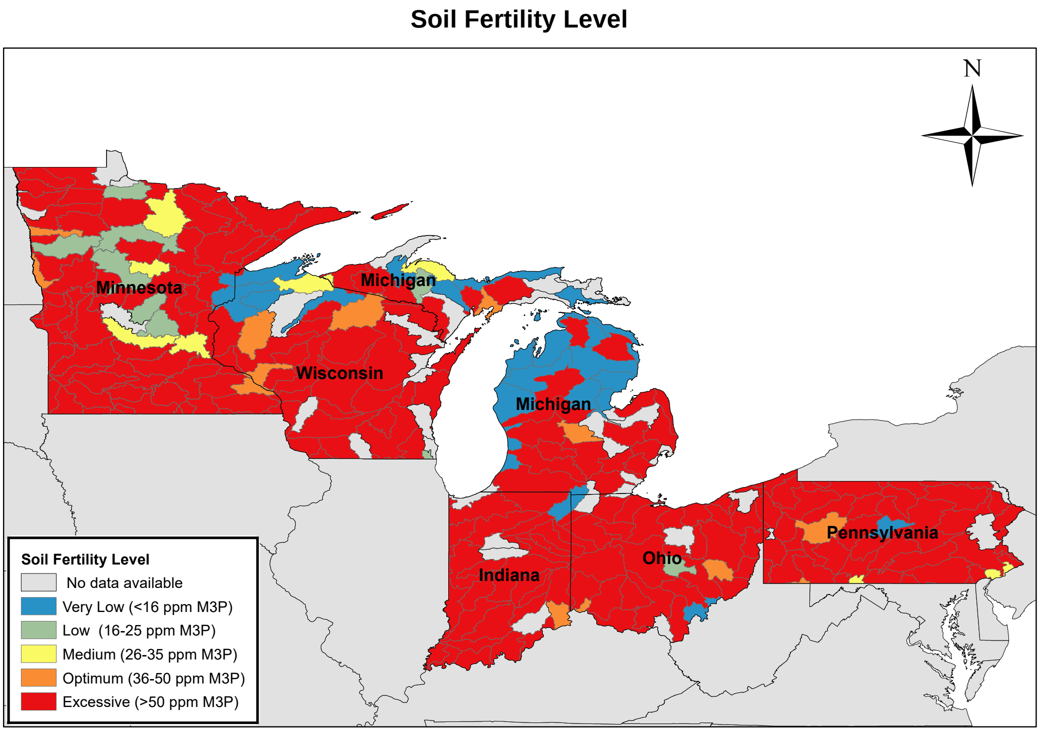


Figure 3S: Soil Fertility Level in the contiguous US at a HUC8 spatial resolution

2 Framework development

2.1 Data entry

Table 3S: Livestock waste composition and generation rates for different types of animals (Kellogg et al., 2000; United States Department of Agriculture (USDA), 2009).

Livestock type	Water (%wt)	Organic matter (%wt)	Total N (%wt)	Total P (%wt)	Total Ca (%wt)	Total K (%wt)	Generation rate (kg/day)	Animal unit equivalence
Dairy cow	87	10,98	0,59	0,08	0,12	0,20	37,88	0,74
Dairy heifer	83	13,04	0,48	0,09	0,12	0,21	29,95	0,94
Dairy calf	83	9,28	0,51	0,06	0,12	0,13	29,95	4,00
Beef cow	88	10,58	0,34	0,08	0,12	0,24	28,58	1,00
Beef calf	88	10,00	0,58	0,10	0,12	0,38	28,14	4,00

Table 4S: Predefined economic parameters.

Parameter	Value
Discount rate (%)	7
Phosphorus credits (USD / kg P recovered)	22
Electricity price (Renewable Energy Certificates) (USD/MWh)	60
Bio-methane price (Renewable Identification Number) (USD/kg)	1.25
Capital cost incentive (% over total capital cost)	0

2.2 Techno-economic model

2.2.1 Manure conditioning model

U.S. EPA determines that the content of total solids in manure should be less than 15%, as shown in Fig. 4S (U.S. Environmental Protection Agency, 2004). Therefore, additional water may be added to reduce the solids content in manure before the anaerobic digestion stage.

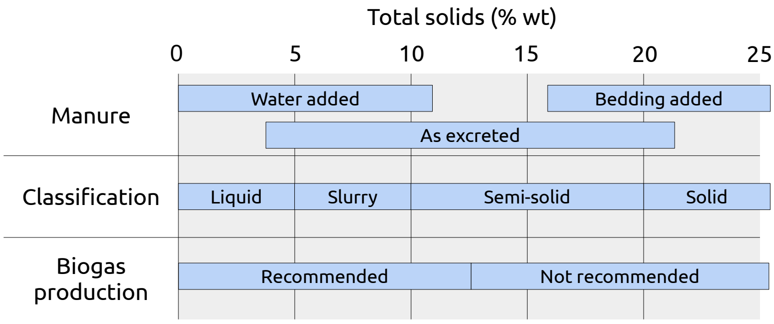


Figure 4S: Adequate manure properties for anaerobic digestion. Adapted from U.S. Environmental Protection Agency (2004).

2.2.2 Anaerobic digestion model

Table 5S: Statistical summary of nutrients composition for cattle manure before and after anaerobic digestion (AD). All concentrations are reported in mg/L. TKN is referrered to total Kjeldahl nitrogen, and TP to total phosphorus. Data from K. Smith et al. (2007); Martin (2003); Alburquerque et al. (2012); Sørensen et al. (2011).

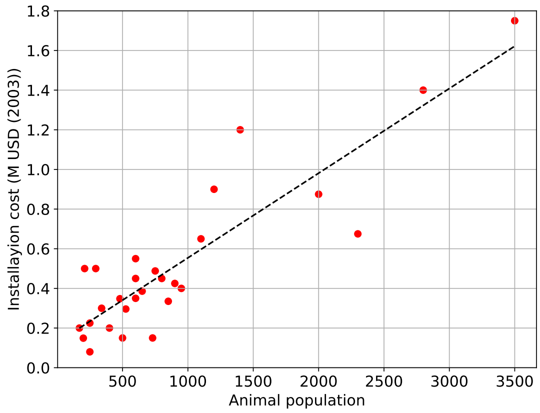
	TKN before AD	TKN after AD	NH_4 before AD	NH_4 after AD	TP before AD	NH_4 after AD	P-PO_4 before AD	P-PO_4 after AD
count	10.00	10.0	10.00	10.00	5.00	5.00	5.00	5.00
mean	3856.10	3967.1	1845.90	2340.10	1442.60	1449.60	811.40	946.40
std	847.41	942.9	354.59	387.34	467.14	485.29	277.67	331.88
min	2920.00	2800.0	1300.00	1810.00	813.00	838.00	457.00	562.00
25%	3050.00	3152.5	1607.50	2047.50	1170.00	1170.00	590.00	670.00
50%	3660.00	3855.0	1825.00	2340.00	1450.00	1360.00	880.00	950.00
75%	4630.75	4882.5	2159.75	2590.00	1860.00	1920.00	1050.00	1260.00
max	4960.00	5290.0	2300.00	2881.00	1920.00	1960.00	1080.00	1290.00

Correlations to estimate the capital cost, Eq. 4, and operating and management costs (O&M), Eq. 5, as a function of the animal population of CAFOs were developed using data from the US EPA AgSTAR program (U.S. Environmental Protection Agency, 2003) and the USDA (Beddoes et al., 2007) respectively, as shown in Figure 5S. 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 the O&M costs, Eq. 6. The assumed equipment lifetime is 20 years.

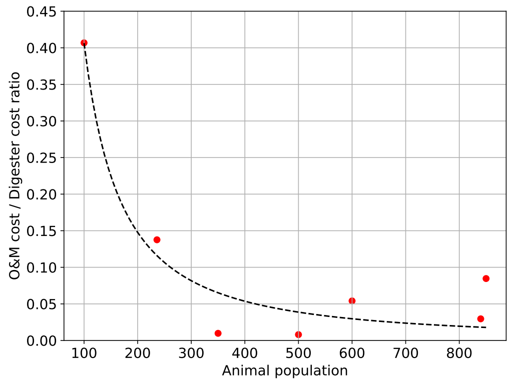
$$\text{Installation cost (MM USD (2019))} = \left(4.271 \cdot 10^{-4} \cdot N_{animals} + 0.127\right) \cdot 1.511 \tag{4}$$

$$\frac{\text{O\&M}}{\text{Installation cost}} \text{ ratio} = \frac{15.858 \cdot 10^{3}}{\left(1 + \left(N_{animals} \cdot 13.917\right)^{1.461}\right.} \tag{5}$$

$$\text{Operating cost} = \text{O\&M costs} + \frac{\text{Investment cost}}{\text{Plant lifetime}} \tag{6}$$



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



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

Figure 5S: Correlations between AD capital and O&M costs, and the number of cattle in the livestock facility.

2.2.3 Solid-liquid separation model

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 partition coefficients for the different components are shown in Table 6S.

Table 6S: 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 7S. 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. 6S and Table 8S.

Table 7S: Sizing estimated for screw press units based commercial on data (PWTech Process Wastewater Technologies LLC., 2018)

Load capacity $\left(\frac{m^3}{day}\right)$	Number of units			
	$\varnothing$(m) 0.23	$\varnothing$(m) 0.35	$\varnothing$(m) 0.42	$\varnothing$(m) 0.56
< 43	1	-	-	-
43 - 81	-	1	-	-
81 - 190	-	-	1	-
190 - 381	-	-	2	-
381 - 572	-	-	3	-
572 - 708	-	-	-	2
708 - 1090	-	-	-	3
1090 - 1444	-		-	4
> 1444	-	-	-	$\left\lceil \frac{\text{Flow } (m^3/day)}{\text{Load Capacity}_{\varnothing 0.56\text{m unit}}} \right\rceil$

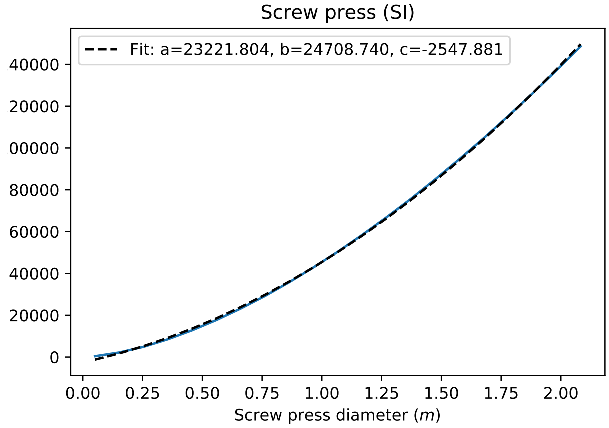
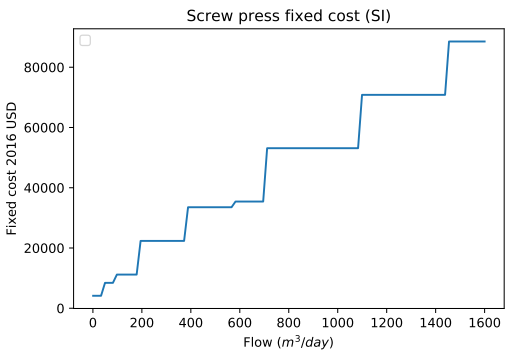


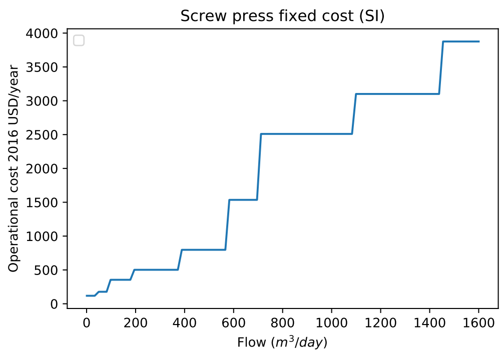
Figure 6S: Estimated screw press investment costs (USD) as a function of the size.

Table 8S: Electrical power of screw press units (PWTech Process Wastewater Technologies LLC., 2018)

Number of units	Electrical power (kW)			
	⌀(m) 0.23	⌀(m) 0.35	⌀(m) 0.42	⌀(m) 0.56
1	0.3	0.45	0.9	-
2	-	-	1.27	3.88
3	-	-	2.01	6.34
4	-	-	-	7.83



(a) Estimated investment costs for screw press units.



(b) Estimated operation costs for screw press units.

Figure 7S: Estimated capital and operating costs for screw press units.

2.2.4 Nutrient recovery model

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. 7 to 9, where $x_{Ca^{2+}:PO_4^{3-}}$ refers to the Ca^{2+}/PO_4^{3-} molar ratio, $x_{struvite\left(PO_4^{3-}\right)}$ is the fraction of phosphorus as phosphate recovered as struvite, and $x_{HAP(Ca^{2+})}$ and $x_{CaCO_3(Ca^{2+})}$ are the fraction of calcium recovered as hydroxyapatite and calcium carbonate respectively.

$$x_{Struvite} = \frac{0.798}{1 + \left(x_{Ca^{2+}:PO_4^{3-}} \cdot 0.576\right)^{2.113}} \cdot 100 \tag{7}$$

$$\begin{aligned} x_{HAP} = \big(& -4.321 \cdot 10^{-2} \cdot x^2_{Ca^{2+}:PO_4^{3-}} + 0.313 \cdot x_{Ca^{2+}:PO_4^{3-}} \\ & - 3.619 \cdot 10^{-2}\big) \cdot 100 \end{aligned} \tag{8}$$

$$x_{CaCO_3} = \frac{1.020}{1 + \left(x_{Ca^{2+}:PO_4^{3-}} \cdot 0.410\right)^{1.029}} \cdot 100 \tag{9}$$

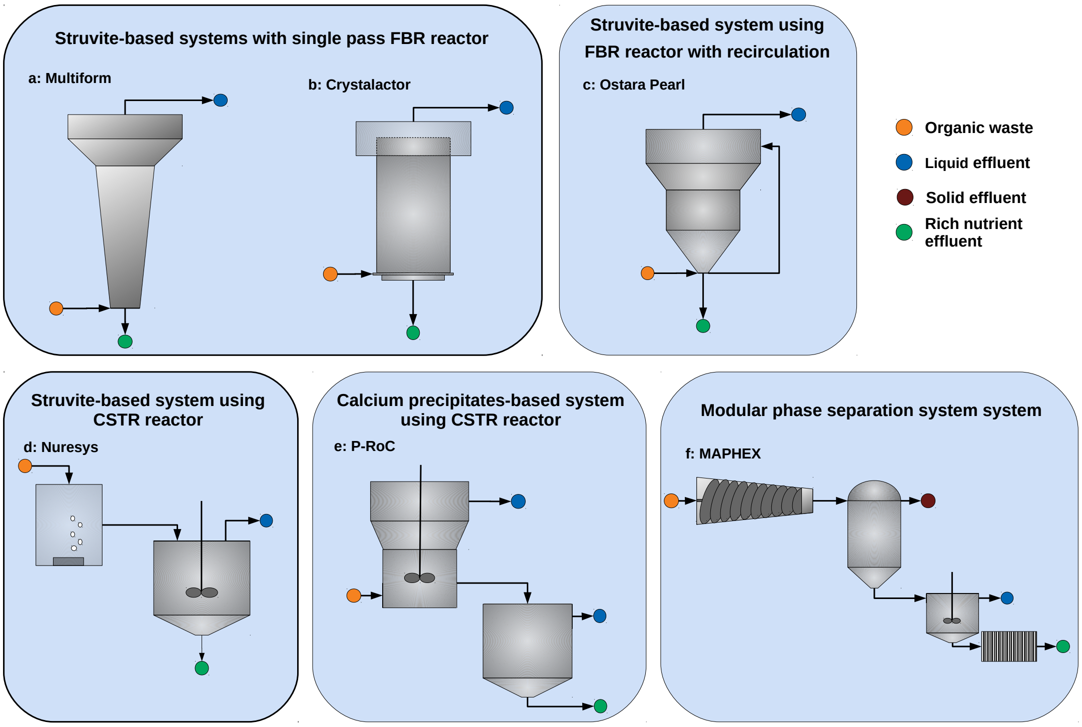


Figure 8S: Flowsheets of the nutrient recovery systems considered in the proposed framework. a: Multiform, b: Crystalactor, c: Ostara Pearl, d: Nuresys, e: P-RoC, f: MAPHEX.

2.2.4.1 Phosphorus recovery as struvite in single pass FBR reactor: Multiform Harvest and Crystalactor. Phosphorus can be recovered in the form of struvite using single pass fluidized bed reactors (FBR). Multiform Harvest and Crystalactor are commercial technologies using this configuration, based on single pass fluidized bed reactors, with no recirculation and conical or cylindrical design respectively, where the organic waste is pumped, carrying out the struvite formation. The struvite particles grow, increasing their size, until their mass overcome the drag force of the uplift stream.

Multiform, Fig. 8Sa, is a nutrient recovery system developed by the U.S. based company Multiform Harvest. It is a struvite-based process designed to be simple, robust, and fully automatized. Large struvite particles settle towards the reactor base, from where they are removed to be dried before obtaining the final product. $MgCl_2$ is supplied to the reactor for increasing struvite supersaturation, enhancing its precipitation. pH is adjusted using sodium hydroxide. The conical design of the reactor keeps the small and lighter particles on the large diameter section at the top of the reactor, where the superficial velocity is slower. As the particles increase their mass, they settle gradually to lower levels of the reactor, where the diameter is smaller and the superficial velocity and drag force larger, until they are finally settled on the bottom of the reactor. The liquid phase exits the reactor from the top, where the cross-section is the widest, to ensure the retention of struvite fines (Australian Meat Processor Corporation, 2018). The techno-economic model for the Multiform process considers a unique size able to process up to 38.5 kg of phosphorus (P-PO_4) per day, with an associated capital cost of 625,000 USD per each Multiform unit, plus 420,000 USD for the struvite dryer that serves all Multiform units. The operating cost for the Multiform system unit is 15.419 USD per kg of P-PO_4 processed (Australian Meat Processor Corporation, 2018).

Crystalactor is a nutrient recovery system created by the Dutch company Royal HaskoningDHV, Fig. 8Sb. It is based on a fluidized bed reactor where phosphorus is recovered as precipitates. It can be configured to recover phosphate in the form of calcium phosphates or struvite, depending on the reactant supplied. The model included in the framework considers that the system is configured for struvite production since struvite has a more consolidated market than calcium precipitates to sell the final product recovered. Under this configuration, the reactor is filled with small struvite particles playing the role of seeds to promote the precipitation process, and $MgCl_2$ is supplied to increase struvite supersaturation (Egle et al., 2016). It is considered that each unit is able to process up to 137.7 kg of P-PO_4 per day. The economy of scale for Crystalactor costs can be captured through the previous work developed by Egle et al. (2016) using Eq. 10, where $n_{\text{Crystalactor}}$ represents the number of Crystalactor units installed. Crystalactor operating cost assumed is 2.12 USD per kg of P-PO_4 processed (Egle et al., 2016).

$$\text{Capital cost}_{\text{Crystalactor}} = 2.3 \cdot 10^6 + 714,285.71 \cdot n_{\text{Crystalactor}} \tag{10}$$

2.2.4.2 Phosphorus recovery as struvite in a FBR reactor with recirculation: Ostara Pearl. Pearl is a struvite-based nutrient recovery system developed by the Canadian company Ostara, Fig. 8Sc. The system is based on a continuous operated fluized bed reactor (FBR) reactor where the waste stream is in contact with struvite particles, which promotes the precipitation of struvite. To increase the supersaturation of struvite and enhance its precipitation, $MgCl_2$ is supplied to the reactor in a molar ratio of 2 mol of Mg per mol of phosphate. pH is adjusted using sodium hydroxide. In the reactor, the struvite particles grow until they reach a critical mass enough to overcome the drag force of the uplift liquid. To achieve different superficial velocities along the reactor, the diameter of the reactor increases with the height, providing sufficient superficial velocity in the bottom of the vessel to fluidize the struvite seeds, while the larger diameter in the top of the reactor reduces the liquid uplift velocity, allowing retention of fine crystal seed particles in the reactor. Large struvite particles sink towards the base of the reactor, from where they are periodically withdrawn. To increase the liquid flow in the reactor and achieve larger superficial velocities, an internal recirculation loop is used to recirculate liquid to the bottom of the reactor. A drying step is performed to remove the excess of moisture contained in the struvite particles obtained from the reactor. The liquid stream leaves the reactor at the top, where the cross-section has the largest diameter to ensure the retention of struvite fines.

Based on the information reported by Ostara (Australian Meat Processor Corporation, 2018), standard equipment sizes for the Pearl system are divided in three different capacities, Pearl 500, Pearl 2K, and Pearl 10K, with a load capacities range from 65 to 1250 kg PO_4 per day, as shown in Table 9S. Investment and operation costs for the Ostara Pearl process, including the cost of the conveyor dryer included in the process, can be found in Table 9S (Napa Sanitation District. County of Napa, n.d.; Ohio Water Environment Association, n.d.; Australian Meat Processor Corporation, 2018; American Society of Civil Engineers (ASCE), 2013). A investment cost-equipment cost ratio of 1.9 has been considered (Australian Meat Processor Corporation, 2018).

Table 9S: Sizing and equipment cost estimated for Ostara Pearl process

	Pearl 500	Pearl 2K	Pearl 10K
Load capacity $\left(\frac{kg_{P\text{-}PO_4}}{day}\right)$	65	250	1250
Capital cost (USD)	$2.3 \cdot 10^6$	$3.1 \cdot 10^6$	$10.0 \cdot 10^6$
$\frac{\text{Investment}}{\frac{kg_{PO_4}}{\text{day}}}$ $\left(\frac{USD}{kg}\right)$	35,385	12,252	8,000

2.2.4.3 Phosphorus recovery as struvite in a CSTR reactor: NuReSys.

NuReSys, Fig. 8Sd is a nutrient recovery technology develop in Belgium by Nutrients Recovery Systems. Struvite formation is carried out in a continuous stirred tank reactor (CSTR), equipped with a special impeller to minimize the breakage of struvite crystals. NuReSys process uses a stripper as pretreatment where air is injected in the organic waste, decomposing organic carbon and increasing the pH. If pH adjustment is needed, sodium hydroxide is added to the CSTR vessel. The liquid stream is fed into the CSTR reactor for struvite precipitation. Similar to other struvite-based processes, $MgCl_2$ is supplied to the reactor to increase struvite supersaturation. After struvite precipitation, both solid and liquid phases are extracted from the reactor in the same stream and it is injected in a settler where the separation of phases is carried out. Struvite fines are separated from the largest struvite particles through a hydrocyclone and they are recirculate to the process. The struvite particles are dried before their final collection (Australian Meat Processor Corporation, 2018).

Considering the data available, it has been assumed that each NuReSys system unit is able to process up to 204 kg of P-PO_4 per day, with an associated capital cost of 1,380,655 USD. NuReSys operating cost is 6.22 USD per kg of P-PO_4 processed (Australian Meat Processor Corporation, 2018).

2.2.4.4 Phosphorus recovery as calcium precipitates in CSTR a reactor: P-RoC.

P-RoC is a patented system by the Karlsruhe Institute of Technology (Germany) for phosphorus recovering as calcium precipitates, Fig. 8Se. P-RoC is based on a reactive substrate, calcium-silicate hydrate (CSH), which is the support on which phosphorus is deposited forming a calcium precipitate. The process is carried out in a CSTR reactor, where the precipitates are formed. Liquid and solid phases are separated by sedimentation in a settler, and the obtained particles are finally dried in two consecutive steps composed by a belt filter and a conveyor dryer (Ehbrecht et al., 2011).

As P-RoC is not yet a fully commercial technology, the capital cost is estimated through a preliminary design of each equipment: CSTR reactor, settler, and belt dryer. The estimation of the investment of the CSTR reactor unit is the result of the sum of the vessel and the agitator costs. For design purposes, a maximum CSTR volume of 45 m^3 is considered (Turton, R., 2010).

For larger volumes, multiple units installed in parallel are considered, Eq. 11. The vessel cost is based on data reported by CAPCOST (Turton, R., 2010), from which the correlation shown in Fig. 9S has been developed.

$$\text{Number of CSTR} = \left\lceil \frac{\text{Total volume}}{\text{Max. sixe}} \right\rceil \tag{11}$$

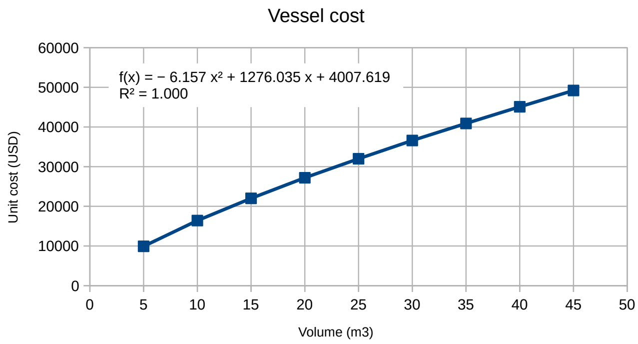


Figure 9S: Estimated investment costs for a non-jacketed vessel, based on data from CAPCOST (Turton, R., 2010).

The clarifier cost has been estimated as a vessel, using the correlation shown in Fig. 9S. The residence time assumed is 1 hour (Ehbrecht et al., 2011). A vacuum conveyor filter has been selected for struvite recovery from the outlet reactor stream since previous studies report the use of this equipment (Matynia et al., 2013). For design purposes, a filter rate of 0.011 kg/(m^2·s) and a maximum area of 1,200 ft^2 are considered (Couper et al., 2012). The unit cost is based on the correlations reported in Couper et al. (2012). This correlation is based on the area of the filter. Vacuum conveyor filter area and cost are collected in Eqs. 12 and 13. The final drying of struvite is achieved with a conveyor dryer. For design purposes, a drying time of 2,100 s and a dryer capacity of 20.85 kg/m^2 are assumed based on data reported on Table 12-21 of Perry and Green (2007). The dryer loading and dryer area are estimated using Eqs. 14 and 15, respectively.

$$\text{Area}_{\text{filter}}\ \left(m^2\right) = \frac{Flow\left(\frac{kg}{s}\right)}{Rate_{filtration}\left(\frac{kg}{m^2\cdot s}\right)} \tag{12}$$

$$\text{Filter cost}\ \left(2009\ USD\right) = \frac{45506}{Area_{filter}^{0.5}\left(ft^2\right)}\cdot Area_{filter}\left(ft^2\right) \tag{13}$$

$$\text{Loading}_{\text{dryer}}\ \left(kg\right) = Flow\left(\frac{kg}{s}\right)\cdot time_{drying}\left(s\right) \tag{14}$$

$$\text{Area}_{\text{dryer}}\ \left(m^2\right) = \frac{Loading_{dryer}\left(kg\right)}{Capacity_{dryer}\left(\frac{kg}{m^2}\right)} \tag{15}$$

The cost estimation for a conveyor unit is based on data reported in Table 12-23 of Perry and Green (2007). The correlation developed, relating the unit cost and its area can be found in Fig. 10S. Additionally, based on these data, a maximum conveyor dryer size of 90 m^2 is assumed.

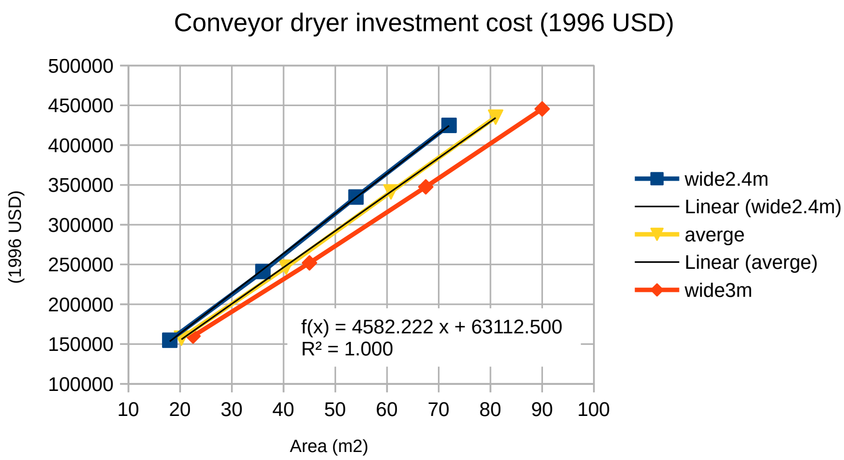


Figure 10S: Estimated investment costs for conveyor dryer unit.

Based on data reported by Egle et al. (2016), it has been considered that operation costs are variable as a function of the processed amount of P-PO_4. as it is shown in Eq. 16, where

x_{P-PO_4} represents the kg of P-PO_4 processed per day

$$\text{Operation Cost}_{\text{P-RoC}}\left(\frac{USD}{kg_{P-PO_4}}\right) = \begin{cases} 115.5, & \text{if } x_{P-PO_4} < 135 \\ -0.09 \cdot x_{P-PO_4} + 127.19, & \text{if } 135 \geq x_{P-PO_4} \geq 662 \\ 67.9, & \text{if } x_{P-PO_4} > 662 \end{cases} \quad (16)$$

2.2.4.5 Phosphorus recovery through a modular phases separation system: MAPHEX.

MAPHEX is a nutrient recovery system based on physico-chemical separations developed by Penn State University and the USDA, Fig. 8Sf. It involves three stages: liquid-solid separation with an screw press and a centrifuge, addition of iron sulfate to improve nutrients retention, and filtration with diatomaceous earth as filter media. It is conceived as a mobile modular system which can be set in two interconnected truck trailers (Church et al., 2016, 2018). Each MAPHEX unit is able to process up to 18.54 kg of P-PO_4 fed per day, with an associated operation cost of 110.8 USD per kg of P-PO_4 processed. Capital cost of a MAPHEX unit is 291,000 USD (Church et al., 2016, 2018).

3 Multi-criteria decision model

In the SMAA method, 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. Fig. 11S shows the feasible weight space for a problem with three criteria.

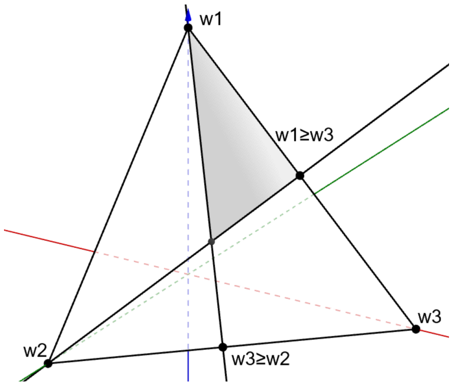


Figure 11S: Example of feasible weights space for a three criteria problem considering ranking of criteria. Figure adapted from Tervonen and Lahdelma (2007)

4 Description of the Great Lakes area

Table 10S: Livestock residues and phosphorus releases by concentrated animal operation in the Grat Lakes area, year 2019. (Indiana Department of Environmental Management, 2019; Ohio Department of Agriculture, 2019; Pennsylvania Department of Environmental Protection, 2019; Wisconsin Department of Natural Resources, 2019; Minnesota Center for Environmental Advocacy, 2019; Michigan Department of Environment, Great Lakes, and Energy, 2019)

	Pennsylvania	Ohio	Indiana	Michigan	Minnesota	Wisconsin
Total animal units	195,967	128,008	187,355	354,460	943,094	743,777
Manure generated (kg/year)	$2.60{\cdot}10^{9}$	$1.68\ {\cdot}10^{9}$	$2.48{\cdot}10^{9}$	$4.76{\cdot}10^{9}$	$1.13{\cdot}10^{10}$	$1.03{\cdot}10^{10}$
Phosphorus releases (kg/year)	$2.07{\cdot}10^{6}$	$1.34{\cdot}10^{6}$	$1.98{\cdot}10^{6}$	$3.80{\cdot}10^{6}$	$9.02{\cdot}10^{6}$	$8.20{\cdot}10^{6}$
Dairy Animal units	167,247	101,341	153,495	311,553	428,459	731,927
Manure generated from dairy cows (kg/year)	$2.29{\cdot}10^{9}$	$1.40{\cdot}10^{9}$	$2.12{\cdot}10^{9}$	$4.31{\cdot}10^{9}$	$5.95{\cdot}10^{9}$	$1.01{\cdot}10^{10}$
Phosphorus released from dairy cows(kg/year)	$1.83{\cdot}10^{6}$	$1.12{\cdot}10^{6}$	$1.70{\cdot}10^{6}$	$3.45{\cdot}10^{6}$	$4.76{\cdot}10^{6}$	$8.10{\cdot}10^{6}$
Beef animal units	29,370	26,667	33,860	42,907	51,4635	12,088
Manure generated from beef cows (kg/year)	$3.02{\cdot}10^{8}$	$2.78{\cdot}10^{8}$	$3.53{\cdot}10^{8}$	$4.48{\cdot}10^{8}$	$5.33{\cdot}10^{9}$	$1.26{\cdot}10^{8}$
Phosphorus released from beef cows(kg/year)	$2.42{\cdot}10^{5}$	$2.23{\cdot}10^{5}$	$2.83{\cdot}10^{5}$	$3.58{\cdot}10^{5}$	$4.26{\cdot}10^{6}$	$1.01{\cdot}10^{5}$

References

Alburquerque, J., de la Fuente, C., & Bernal, M. (2012). Chemical properties of anaerobic digestates affecting c and n dynamics in amended soils. *Agric. Ecosyst. Environ.*, *160*, 15-22.

Allen, B. L., & Mallarino, A. P. (2006). Relationships between extractable soil phosphorus and phosphorus saturation after long-term fertilizer or manure application. *Soil Sci. Soc. Am. J.*, *70*, 454–463. doi: 10.2136/sssaj2005.0031

American Society of Civil Engineers (ASCE). (2013). *Chicago to Add Nutrient Recovery to Largest Plant.* `https://www.asce.org/magazine/20131105-chicago-to-add-nutrient-recovery-to-largest-plant/`. ([Online; accessed 21-March-2019])

Australian Meat Processor Corporation. (2018). *Struvite or Traditional Chemical Phosphorus Precipitation – What Option Rocks?* `https://www.ampc.com.au/uploads/cgblog/id408/2018-1026_-_Final_Report.pdf`. ([Online; accessed 20-March-2019])

Beddoes, J. C., Bracmort, K. S., Burns, R. T., & Lazarus, W. F. (2007). *An analysis of energy production costs from anaerobic digestion systems on u.s. livestock production facilities* (Tech. Rep.). U.S. Department of Agriculture (USDA).

Carlson, R. E. (1977, March). A trophic state index for lakes: Trophic state index. *Limnol. Oceanogr.*, *22*(2), 361–369. Retrieved 2019-10-17, from `http://doi.wiley.com/10.4319/lo.1977.22.2.0361` doi: 10.4319/lo.1977.22.2.0361

Church, C. D., Hristov, A. N., Bryant, R. B., Kleinman, P. J. A., & Fishel, S. K. (2016, February). A Novel Treatment System to Remove Phosphorus from Liquid Manure. *Appl. Eng. Agric.*, *32*(1), 103–112. Retrieved 2019-09-13, from `http://elibrary.asabe.org/abstract.asp?aid=46616&t=3&dabs=Y&redir=&redirType=` doi: 10.13031/aea.32.10999

Church, C. D., Hristov, A. N., Kleinman, P. J., Fishel, S. K., Reiner, M. R., & Bryant, R. B. (2018). Versatility of the MAnure PHosphorus EXtraction (MAPHEX) System in Removing Phosphorus, Odor, Microbes, and Alkalinity from Dairy Manures: A Four-Farm Case Study. *Applied Engineering in Agriculture*, *34*(3), 567–572. Retrieved 2019-09-13, from `http://elibrary.asabe.org/abstract.asp?AID=48976&t=3&dabs=Y&redir=&redirType=` doi: 10.13031/aea.12632

Couper, J. R., Penney, W. R., Fair, J. R., & Walas, S. M. (2012). *Chemical process equipment (third edition)* (Third Edition ed.). Boston: Butterworth-Heinemann. Retrieved from `http://www.sciencedirect.com/science/article/pii/B978012396959000032X` doi: https://doi.org/10.1016/B978-0-12-396959-0.00032-X

Dzombak, D. A. (2011). Nutrient Control in Large-Scale U.S. Watersheds. *The Bridge*, *41*(4), 13–22.

Egle, L., Rechberger, H., Krampe, J., & Zessner, M. (2016, November). Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. *Science of The Total Environment*, *571*, 522–542. Retrieved 2019-09-13, from `https://linkinghub.elsevier.com/retrieve/pii/S0048969716314656` doi: 10.1016/j.scitotenv.2016.07.019

Ehbrecht, A., Schönauer, S., Fuderer, T., & Schuhmann, R. (2011, January). P-Recovery from sewage by seeded crystallisation in a pilot plant in batch mode technology. *Water Science and Technology*, *63*(2), 339–344. Retrieved 2019-10-17, from `https://iwaponline.com/wst/article/63/2/339/13814/PRecovery-from-sewage-by-seeded-crystallisation-in` doi: 10.2166/wst.2011.061

Espinoza, L., Slaton, N. A., & Mozaffari, M. (2006). *Understanding the numbers on your soil test report* (Tech. Rep.).

Indiana Department of Environmental Management. (2019). *Confined Feeding Operation Facilities (20200402).* `https://maps.indiana.edu/previewMaps/Environment/Agribusiness_Confined_Feeding_Operations.html`. ([Online; accessed 29-July-2019])

International Plant Nutrition Institute (IPNI). (2012). *A Nutrient Use Information System (NuGIS) for the U.S.* (Tech. Rep.). International Plant Nutrition Institute (IPNI).

Kadlec, R. (2016). Large constructed wetlands for phosphorus control: A review. *Water*, *8*, 243.

Kellogg, R. L., Lander, C. H., Moffitt, D. C., & Gollehon, N. (2000). *Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States* (Tech. Rep.). United States Department of Agriculture (USDA).

Martin, J. (2003). *A comparison of dairy cattle manure management with and without anaero-*

bic digestion and biogas utilization (Tech. Rep.). AgSTAR Program, U.S. Environmental Protection Agency.

Martín-Hernández, E., Ruiz-Mercado, G., & Martín, M. (2020). Model-driven spatial evaluation of nutrient recovery from livestock leachate for struvite production. *J. Environ. Manage.*, *271*, 110967.

Matches. (2014). *Matches' process equipment cost estimates.* https://matche.com/equipcost/Default.html. ([Online; accessed 29-March-2018])

Matynia, A., Wierzbowska, B., Hutnik, N., Mazienczuk, A., Kozik, A., & Piotrowski, K. (2013). Separation of struvite from mineral fertilizer industry wastewater. *Procedia. Environ. Sci.*, *18*, 766-775.

Michigan Department of Environment, Great Lakes, and Energy. (2019). *Active NPDES Permits.* https://www.michigan.gov/egle/0,9429,7-135-3313_72753-10780--,00.html. ([Online; accessed 29-July-2019])

Minnesota Center for Environmental Advocacy. (2019). *Minnesota Confined Animal Feeding Operations.* http://www.mncenter.org/agriculture.html. ([Online; accessed 29-July-2019])

Møller, H., Lund, I., & Sommer, S. (2000). Solid-liquid separation of livestock slurry: effciency and cost. *Bioresour. Technol.*, *74*, 223-229.

Napa Sanitation District. County of Napa. (n.d.). *Phosphorus recovery.* http://services.countyofnapa.org/agendanet/DownloadDocument.aspx?type=NAPASAN&doctype=ATTACHMENT&id=27457. ([Online; accessed 20-March-2019])

Ohio Department of Agriculture. (2019). *Livestock Environmental Permitting.* Personal Communication.

Ohio Water Environment Association. (n.d.). *A Green Alternative for Dissolved Nutrient Recovery in Wastewater Side Streams.* http://www.ohiowea.org/docs/01_EcoAlternative_Nutrient_Recovery.pdf. ([Online; accessed 20-March-2019])

Pennsylvania Department of Environmental Protection. (2019). *Concentrated Animal Feeding Operations.* https://www.dep.pa.gov/Business/Water/CleanWater/AgriculturalOperations/CAFOs/pages/default.aspx. ([Online; accessed 29-July-2019])

Perry, R., & Green, D. (2007). *Perry's chemical engineers' handbook.* McGraw-Hill.

Pickard, B. R., Daniel, J., Mehaffey, M., Jackson, L. E., & Neale, A. (2015). Enviroatlas: A new geospatial tool to foster ecosystem services science and resource management. *Ecosyst. Serv.*, *14*, 45-55.

PWTech Process Wastewater Technologies LLC. (2018). *Volute Dewatering Press* (Tech. Rep.). PWTech Process Wastewater Technologies LLC.

Smith, D. B., Cannon, W. F., Woodruff, L. G., Solano, F., Kilburn, J. E., & Fey, D. L. (2013). *Geochemical and Mineralogical Data for Soils of the Conterminous United States: U.S. Geological Survey Data Series 801* (Tech. Rep.). U.S. Geological Survey (USGS).

Smith, K., Grylls, J., Metcalfe, P., Jeffrey, B., & Sinclair, A. (2007). *Nutrient Value of Digestate from Farm-Based Biogas Plants in Scotland* (Tech. Rep.). Scottish Executive Environment and Rural Affairs Department.

Sørensen, P., Mejnertsen, P., & Møller, H. (2011). Nitrogen fertilizer value of digestates from anaerobic digestion of animal manures and crops. *NJF Report*, *7*(8), 42-44.

Tervonen, T., & Lahdelma, R. (2007, April). Implementing stochastic multicriteria acceptability analysis. *European Journal of Operational Research*, *178*(2), 500–513. Retrieved 2019-10-02, from https://linkinghub.elsevier.com/retrieve/pii/S0377221706000506 doi: 10.1016/j.ejor.2005.12.037

Turton, R. (2010). *CAPCOST software to accompany: Analysis, synthesis, and design of chemical processes* (Tech. Rep.). Upper Saddle River, N.J: Prentice Hall PTR.

United States Department of Agriculture. (2009). *Waste Management Field Handbook* (Tech. Rep.). United States Department of Agriculture.

United States Department of Agriculture. (2019). *2017 Census of Agriculture. United Satates. Summary and State Data* (Tech. Rep.). United States Department of Agriculture.

United States Department of Agriculture (USDA). (2009). *Agricultural Wate Management Field Handbook* (Tech. Rep.). United States Department of Agriculture (USDA).

United States Environmental Protection Agency (USEPA). (2012a). *2012 National Lakes Assessment. Quality Assurance Version Project Plan* (Tech. Rep.). Author.

United States Environmental Protection Agency (USEPA). (2012b). *National Lakes Assessment 2012. A Collaborative Survey of Lakes in the United States* (Tech. Rep.). Author.

United States Environmental Protection Agency (USEPA). (2012c). *National Lakes Assessment. A Collaborative Survey of the Nation's Lakes* (Tech. Rep.). Author.

U.S. Environmental Protection Agency. (2003). *AgSTAR Digest* (Tech. Rep.). U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency. (2004). *AgSTAR Handbook. A Manual For Developing Biogas Systems at Commercial Farms in the United States* (Tech. Rep.). U.S. Environmental Protection Agency.

Wisconsin Department of Natural Resources. (2019). *DNR Runoff Management. CAFO Permittees.* `https://dnr.wi.gov/topic/AgBusiness/data/CAFO/`. ([Online; accessed 29-July-2019])