TYPE Perspective
PUBLISHED 22 July 2022
DOI 10.3389/fceng.2022.970707

OPEN ACCESS

EDITED BY
Fengqi You,
Cornell University, United States

REVIEWED BY
Brenno Menezes,
Hamad bin Khalifa University, Qatar
Ana Inés Torres,
Universidad de la República, Uruguay
Fernando Daniel Mele,
Universidad Nacional de Tucumán,
Argentina

*CORRESPONDENCE
Mariano Martín,
mariano.m3@usal.es

SPECIALTY SECTION
This article was submitted to Computational Methods in Chemical Engineering,
a section of the journal
Frontiers in Chemical Engineering

RECEIVED 16 June 2022
ACCEPTED 30 June 2022
PUBLISHED 22 July 2022

CITATION
Martín-Hernández E, Taifouris M and Martín M (2022), Addressing the contribution of agricultural systems to the phosphorus pollution challenge: a multi-dimensional perspective.
Front. Chem. Eng. 4:970707.
doi: 10.3389/fceng.2022.970707

Addressing the contribution of agricultural systems to the phosphorus pollution challenge: a multi-dimensional perspective

Edgar Martín-Hernández, Manuel Taifouris and Mariano Martín*

Department of Chemical Engineering, University of Salamanca, Salamanca, Spain

The intensification of agricultural systems has increased the food production efficiency, increasing the productivity while the production costs are reduced. Although these factors are key to global food security in a context of continued human population growth, the use of intensive agricultural techniques results in different environmental issues. Mitigating these negative impacts is a requirement for adopting sustainable food production systems. Notably, nutrient pollution is one of the main environmental issues associated with both livestock and crop production. These activities result in different point and non-point source releases of phosphorus, which eventually reach surface and ground waterbodies. This might result in the accumulation of phosphorus over time, contributing to the eutrophication of water ecosystems, and the development of harmful algal bloom (HABs) episodes. The releases of nutrients from agricultural activities can be abated through different management strategies, including the implementation of nutrient recovery techniques at livestock facilities, embracing precision fertilization methods, and developing integrated crop-livestock systems for achieving circular food production systems. In this work, we describe opportunities for Process System Engineering (PSE) to address the development of phosphorus management techniques for mitigating phosphorus pollution from agricultural systems balancing trade-offs between recovery cost and environmental impact mitigation. These techniques integrate the spatial analysis of nutrient pollution from agriculture using geographical information systems (GIS) with the assessment and the selection of phosphorus management techniques combining techno-economic analysis (TEA) and environmental metrics through multi-criteria decision analysis (MCDA) frameworks, and use mathematical programming for the conceptual design of integrated crop-livestock systems.

KEYWORDS

agricultural systems, nutrient pollution, phosphorus recovery, computational methods, process systems engineering (PSE)

1 Introduction

Human development requires the use of natural resources for different purposes from food production to the construction of infrastructures and goods manufacturing. Natural resources can be classified upon their availability at human timescale in renewable and no-renewable resources. A certain natural resource is only considered as renewable if the amount consumed is replenished by natural means at human timescale, while if the replenishment pace is too slow to replace the consumed amount in a finite time at human timescale it is considered as non-renewable. Although the use of renewable natural resources is desirable for sustainability, some non-renewable resources cannot be currently replaced by any renewable resource or synthetic material. This is the case of phosphorus, which is an essential nutrient for food production.

Despite the increase in productivity obtained from the intensive use of phosphorus in agriculture and farming industries (Ashley et al., 2011), multiple environmental impacts emerge from the alteration of the natural cycle of phosphorus (Bouwman et al., 2009). Phosphorus accumulates in soils as a consequence of the continuous application of phosphorus in excess of crop needs, either in the form of synthetic fertilizers or manure, leading to a long-term legacy P (Baligar et al., 2001; Cordell, 2010). Although soils play the role of phosphorus reservoir, since it might be available for future crops, the phosphorus accumulated in soil may eventually be transported to waterbodies through erosion and runoff, representing a source of nutrient pollution. The eutrophication of waters might result in algal blooms altering the normal functioning of aquatic ecosystems and harmful effects, including hypoxia episodes and the release of toxins from some type of algae. These effects negatively impact the environment, but they also represent public health threats restricting the use waterbodies as a source of freshwater for human consumption (Hoagland and Scatasta, 2006).

In addition, the use of phosphorus as an essential nutrient for food production involves a geopolitical dimension as a consequence of the non-renewable nature of this resource, with no synthetic substitute known. Phosphorous reserves are not evenly distributed worldwide, but they are concentrated in a few number of regions, and they are expected to be depleted over the next century (Cordell et al., 2009) assuming the current linear economy paradigm of phosphorus use. This linear economy of phosphorus is based on phosphorus rock mining, which is processed for the manufacturing of fertilizers and livestock feed supplements used in the agricultural sector, and it is finally released to the environment (Jacobs et al., 2017). As a consequence, the supply of phosphorus from a limited number of sources results in a high dependency on a few number of suppliers that jeopardizes the food security and sovereignty of numerous social groups.

The challenges described must be faced in order to develop a sustainable and circular use of phosphorus for food production. The optimization of phosphorus use and the recovery of this material from waste streams could result not only in the mitigation of phosphorus releases into the environment, but phosphorus recycling also contributes to lower dependence on phosphorus imports from other territories and ensures food security.

2 Process systems engineering for phosphorus management in the agricultural sector

Phosphorus management practices can be classified into those strategies for optimizing the use of phosphorus in the agricultural sector and increasing its efficiency, and those actions intended for the recovery of phosphorus from waste flows. Among the first actions, we can list the optimization of the application rate and schedule of fertilizers tailoring the supply of phosphorus to the local requirements of each crop and field, the integration of crop and livestock systems, and the implementation of closed loop greenhouse nutrient feedwater systems; while phosphorus recovery processes can be implemented in some material flows of the agricultural sector such as manure, slaughterhouse waste, and the releases from greenhouse nutrient feedwater systems, as shown in Figure 1.

The study of these practices, shown in Figure 2, including the comparison of phosphorus management techniques, the investment and operating costs associated with them, and the mitigation of environmental impacts achieved through their implementation requires the integration of different methodologies, such as the techno-economic assessment (TEA), life-cycle analysis (LCA), and environmental impact assessment (EIA) of the different phosphorus management practices. The combination of these methodologies with geographical information systems (GIS) and multi-criteria decision analysis (MCDA) techniques result in powerful computational methods for supporting the decision-making processes for the selection of the most suitable phosphorus management strategy for a certain agricultural activity.

2.1 Phosphorus recovery systems

Phosphorus can be recovered and recycled from different streams of the agricultural sector, mainly from manure, slaughterhouse waste, and greenhouse nutrient feedwater systems. Manure is generated in large amounts at livestock facilities, which can be either extensive or intensive production systems. While for extensive farms manure management should not be a concern if the accumulating rates of manure in soil are not excessive, the production of

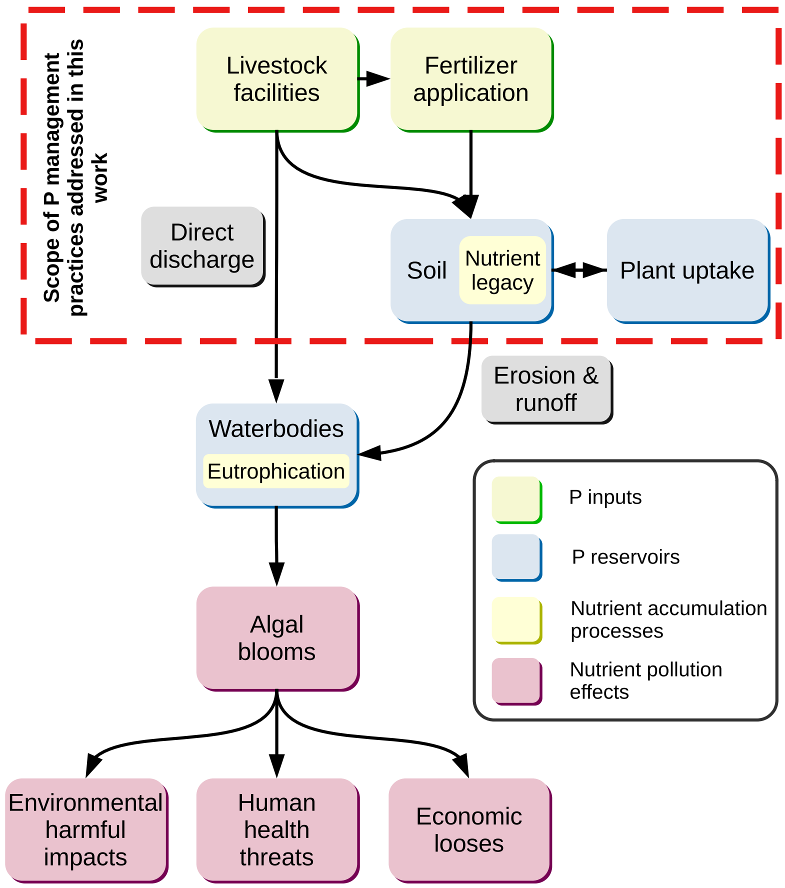

FIGURE 1
Flows of phosphorus used in agriculture.

large amounts of manure at concentrated animal feeding operations (CAFOs) (U.S. Department of Agriculture, 2011) results in an environmental threat due to the release of significant amounts of phosphorus in a single location (Sampat et al., 2017). Although manure can be spread on croplands as a source of phosphorus for crops, it is a bulky material expensive to transport, restricting its application to the croplands in the vicinity of the production site and hindering the redistribution of phosphorus to nutrient deficient locations. Slaughterhouse waste is currently treated before being released into the environment, including the removal of phosphorus. However, phosphorus is removed as sludge and it cannot be further recycled (Australian Meat Processor Corporation, 2018). Finally, the outflows from the greenhouse nutrient feedwater systems might contain phosphorus if they are not recirculated in a closed system, releasing phosphorus into the environment (Ontario Ministry of Agriculture, Food and Rural Affairs, 2021). These flows are point sources of phosphorus, and they can be treated for phosphorus recovery in the form of useful materials such as struvite (Tao et al., 2016) or calcium precipitates (Ehbrecht et al., 2011), providing an opportunity for phosphorus recycling and redistribution to nutrient-deficient areas, creating an effective circular economy around phosphorus.

It should be noted that, although extensive research on phosphorus recovery using processes such as struvite formation has been performed for wastewater (Doyle and Parsons, 2002; Le Corre et al., 2009), there are some factors of agricultural flows that must be considered for phosphorus recovery. Particularly, some characteristics of manure hinder struvite recovery, including the high ionic strength and the presence of calcium (Tao et al., 2016). Therefore, specific physico-chemical or empirical models for phosphorus recovery from agricultural outflows are needed to estimate the performance of these processes (Çelen et al., 2007; Martín-Hernández et al., 2020).

Even though the use of phosphorus recovery technologies in the agricultural sector is a promising approach, their effective implementation faces several significant challenges that requires the use of different computational methods to be addressed. Firstly, there exist different phosphorus recovery technologies at

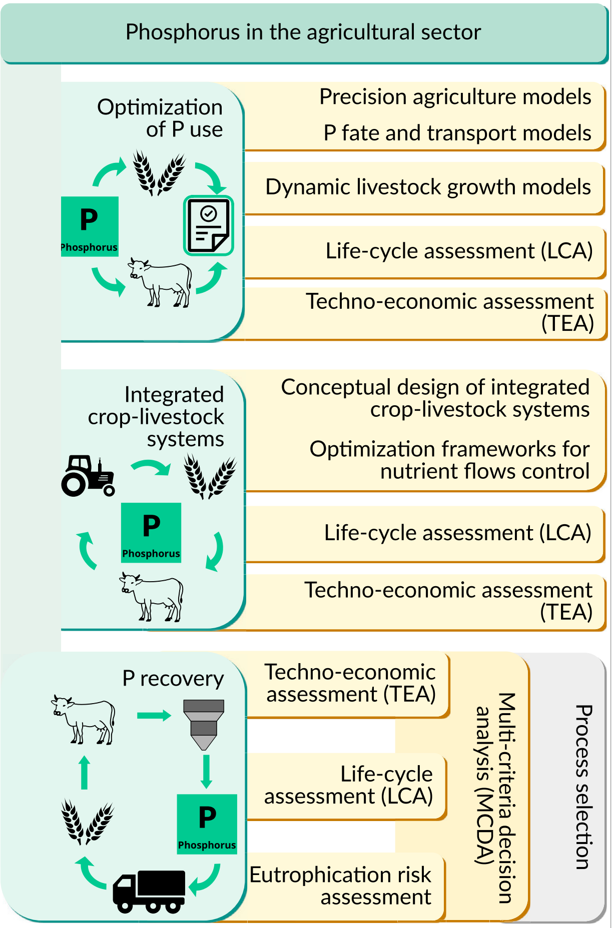

FIGURE 2
Computational methods for the assessment of phosphorus management practices in the agricultural sector.

commercial development stage, and several more at advanced research stages that could be considered for the treatment of phosphorus outflows at a certain facility (Martín-Hernández et al., 2021). Therefore, the decision-making process for the selection of the most suitable phosphorus recovery system for a certain system under evaluation requires the integration of the techno-economic assessment (TEA) of the different technologies available in order to compare their recovery efficiency, investment and operating cost, and in turn to determine the recovery cost of phosphorus, and their life cycle assessment (LCA) to determine the environmental impacts derived from the deployment of each process. Additionally, the current environmental vulnerability to nutrient pollution can be included to provide a holistic framework, determining if the recovery of phosphorus must be more intensive even though involves the implementation of more costly processes through analysis of the local environmental parameters.

If the assessment is performed for a reduced number of facilities, it includes a limited number of recovery processes, and the process selection is made considering a little number of parameters, the information from TEA, LCA, and eutrophication vulnerability studies can be manually analyzed to reach a decision. However, if many processes are considered, or multiple parameters must be analyzed for the selection of the optimal process, the information obtained from the process analyses requires to be assessed through a multi-criteria decision analysis (MCDA) model. These models structure the information for the systematic assessment and comparison of alternatives after defining the relevant criteria (which can be in conflict among them), their relative priority, and the system for criteria evaluation. The goal of an MCDA model is to provide justifiable and explainable solutions aiding in the selection of the most suitable phosphorus recovery process (Belton and Stewart, 2002). Additionally, if the analysis is performed over a region either defined by natural boundaries, such as a watershed, or political borders, such as a county, the framework comprised of TEA, LCA, and environmental evaluation must be embedded in a GIS system to systematically analyze the eutrophication risk of each area. The complete set of information is then provided to an MCDA model to determine the most suitable solution based on the relevant criteria defined.

This scheme has been used in different studies to determine the optimal phosphorus recovery processes for agricultural activities, selection, sizing, and placement of phosphorus recovery processes from livestock waste (Vaneeckhaute et al., 2018; Martín-Hernández et al., 2021), to determine the optimal transportation routes to recover value-added materials and energy from organic waste (Hu et al., 2020), and to design and analyze incentive policies for promoting the implementation of phosphorus recovery processes at CAFOs (Martín-Hernández et al., 2022).

Further challenges must be faced for the effective deployment of phosphorus recovery systems at livestock facilities in which PSE plays a crucial role. Particularly, the scale of livestock facilities is diverse, while the current commercial phosphorus recovery systems are available in fixed sizes. As a consequence, usually the capacity of the units installed for phosphorus recovery does not fit the waste flow to be treated, resulting in suboptimal operation and additional phosphorus recovery costs. Moreover, the economies of scale play a main role in the feasibility of phosphorus recovery processes at livestock facilities, hindering their deployment at small-scale CAFOs. The development of modular and transportable systems could be an alternative for these facilities, so that a single system could be used for the processing of the waste generated in multiple small CAFOs. However, the economic viability of these systems, as well as their optimal routing and scheduling, have to be explored to determine their feasibility and the target facilities on which these processes could be deployed.

2.2 Methods for optimizing phosphorus use in agricultural systems

2.2.1 Crop production

The application rate and schedule of fertilizers, which can be either manure or synthetic fertilizers, are driven by a myriad of factors, including the type of crop, soil properties, weather conditions, etc. Formerly, phosphorus was applied in a excess in order to guarantee that phosphorus was available for crops, resulting in a continuous accumulation of phosphorus in soil over time (Baligar et al., 2001; Cordell, 2010). However, in the last years agriculture precision techniques have been implemented for optimizing the supply of phosphorus to croplands, adjusting the application rate to the requirements of each crop field and selecting the most appropriate application schedule to increase the efficiency of the phosphorus applied (Cisternas et al., 2020). This not only mitigates phosphorus releases into the environment, but also reduces the food production costs. As a result, phosphorus concentration in soils has remained constant over the last 2 decades in the developed countries (International Fertilizer Industry Association, 2007; Probe, 2022), although they are not yet completely implemented in many developing areas (International Fertilizer Industry Association, 2007).

The optimization of phosphorus supply to crops is achieved through the development of models considering soil properties, crop requirements, and weather patterns to determine the available phosphorus in soil and the optimal application rate of fertilizers. The simplest models are empirical correlations relating the supply of phosphorus to crop yields, and sometimes to other related outputs such as greenhouse gas (GHGs) emissions (Chi et al., 2020). These correlations, based on empirical data, can be used to adjust the amount of phosphorus to minimize the cost of fertilizer supply and the environmental impacts. Nevertheless, these models are limited to the particular conditions under which the experimental data were obtained, hindering their use for different field conditions. In order to address these limitations, more general and complex models have been developed through the integration of multiple empirical correlations to evaluate the effect of a large spectrum of factors affecting the growth of crops, including water, nutrients, soil properties, and other environmental conditions on crop growth (Carberry et al., 1989; Basso et al., 2009). This allows adjusting the amount of fertilizer according to the amount of nutrients in the soil or the growth stage of a certain crop. The main drawback of these models is the large amount of information they need, although this can be overcome by combining them with GIS tools and data obtained by on-field sensors (Basso et al., 2007).

In addition to the models for determining the efficient application of fertilizers, the determination of the phosphorus transported from cropfields to waterbodies provides key information for determining what areas are more vulnerable to nutrient pollution, and in turn to define the areas where the phosphorus supply must be more severely controlled and more resources should be directed to control its accumulation and release. Different phosphorus fate and transport models have been proposed in the literature, including but not limited to Spatially Referenced Regression on Watershed Attributes (SPARROW) (Smith et al., 1997), Nutrient Export from Watersheds 2 (NEWS 2) (Mayorga et al., 2010), Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), and Erosion Productivity Impact Calculator (EPIC) (Sharpley, 1990). These models have the potential of being integrated into wider frameworks in order to perform integrated analysis of phosphorus fluxes in a certain area, and different applications of these models have been explored for determining significant contributors to phosphorus releases at watershed level under uncertainty (Kim et al., 2017), as well as the contribution of nutrient flows from croplands, weather patterns and other environmental factors in the occurrence of harmful algal blooms (HABs) and the mitigating effect of implementing phosphorus recovery processes (Hu et al., 2019).

2.2.2 Livestock production

Phosphorus is also an essential nutrient for livestock production, and it is usually supplied through feed crops and synthetic supplements. Since the production of livestock requires large amounts of feeding materials, the optimal selection of the crops used for animal feed has an important role to reduce the consumption of fertilizer by agricultural systems. Some crops exclusively used for animal feed, such as alfalfa or certain types of forage, have higher yields and lower nutrient requirements than cereals. Besides, straws of certain field crops such as barley and wheat can also be used for this purpose, reducing the production of specific crops for livestock feed, and, in turn, the supply of phosphorus needed for the growth of these crops.

Livestock feed must meet the nutritional and energy requirements of each animal attending to its type and life stage. These feeding requirements can be estimated through empirical correlations and yields, resulting in a variety of mathematical models. The simplest ones are based on linear relationships between the animal weight and the feeding requirements (Munford, 1996), while more detailed models are able to tailor the feeding requirements of a certain animal based on defining factors, including breed, sex, stage of growth, and whether it is pregnant or breastfeeding (Council, 2001). The most complete models are not only able to estimate the nutritional requirements, but they can also be used to determine the composition of wastes and animal products through the analysis of the digestion stages. As a result, they can be used to map the phosphorus flows from feed to the production of manure and different animal products such as milk or meat, providing an opportunity to adjust the supply of phosphorus to the requirements of each animal, minimizing the losses of phosphorus from the excessive supply of this material, and thus mitigating the negative environmental impacts of releasing phosphorus into the environment, reducing the production costs as well (Cerosaletti et al., 2004; Knowlton et al., 2004).

2.3 Integrated crop-livestock systems

The separation between the livestock and cropping systems and the intensification of the agricultural techniques have altered the natural cycles of nutrients, resulting in areas with an excessive accumulation of phosphorus in soils causing nutrient pollution, while other regions are deficient on this nutrient (Bouwman et al., 2013). The integration of both systems and the control of nutrient flows, including phosphorus, nitrogen, and potassium between them have been proposed as a solution to close the nutrient loops use since the outputs of one system can be used as inputs in the next (Ellen Mac Arthur Foundation, 2017). Similarly, the recycling of materials between crop and livestock systems can be extended to other essential materials, such as water and carbon sources. This does not only reduce the environmental impact of both sectors, reducing the transport of materials and making more efficient use of nutrients, but also adapts the crops to the nutritional and energy requirements of the animals at each stage of their growth, or conversely, limits the number of animals of the system to the feed that can be supplied by the crops of the close system. Crops can be either grown to obtain food products or as animal feed, while manure and other waste can be used as organic fertilizer, reducing the use of mineral fertilizer and the pollution produced by the transport of feed and waste. As a result, a circular system is developed around the use of phosphorus. However, it must be noted that the integrated crop-livestock systems might not be able to perfectly balance the nutritional requirements of both crops and livestock systems, hence external supplies might be needed, and/or material outflows might occur, although the goal is to minimize the external flows.

The integration of crop production and extensive livestock farming has been widely studied in the literature. In this type of integrated crop-livestock systems, the exchange of phosphorus is carried out through the direct application of manure during animal grazing reducing the requirements of synthetic fertilizer (Peyraud et al., 2014; Salton et al., 2014; Sulc and Franzluebbers, 2014; Sekaran et al., 2021). Conversely, the development of integrated crop production and intensive livestock farming involves an intensive exchange of nutrients, and thus the control of nutrient flows in the system is more critical in order to guarantee that the nutrient releases from the livestock system do not exceed the requirements of crops. The conceptual design of these systems can be performed through the development of frameworks that optimize nutrient flows between intensive livestock and crops system integrating models for estimating the nutritional and energy requirements of the animals, and the nutrient requirements and production yields of crops, as well as the potential integration of nutrient recovery systems for those scenarios where a closed loop of nutrients cannot be achieved (Reddy, 2016). These models, which are described in Section 2.2, often include nonlinear correlations, leading to frameworks comprised of nonlinear programming (NLP) models (Council, 2000).

These models can be used to formulate multi-objective optimization frameworks for the conceptual design of integrated agricultural systems for different objective scenarios such as the maximization of the economic profit of the system, the minimization of the environmental impacts of the system (including the global warming potential, eutrophication potential and the water footprint), or the search of the trade-off solutions between the profitability of the system and the reduction of its environmental impacts, reducing the external supply of phosphorus and the emissions of greenhouse gases (Taifouris and Martin, 2021).

In addition, the design of integrated crop-livestock systems must consider the local environmental context. Therefore, the spatial dimension is a key factor in the design of such facilities since crop yields depend on weather conditions and soil properties, which also determine the availability of nutrients, and thus, the required supply of phosphorus. Moreover, certain locations can be more sensitive to nutrient pollution, which might result in restrictions to the application of fertilizers (either synthetic or manure) and the deployment of nutrient recovery systems, resulting in additional costs and reducing the economic performance of the agricultural systems. The combination of integrated crop-livestock system models with GIS tools results in a new dimension where a large set of potential locations can be evaluated in a supply chain framework in order to determine the optimal location from the economic and environmental perspectives simultaneously. When farm location is an additional variable in the problem, binary variables may be necessary transforming them into mixed-integer linear programming (MILP) or mixed-integer non-linear programming (MINLP) models.

3 Outlook

The implementation of practices for reducing and optimizing the use of phosphorus, as well as the recovery and recycling of the material in the agricultural sector, is crucial to abate the environmental impact of food production and ensure food security and sovereignty reducing the dependency on global supply chains to gain access to phosphorus for agriculture. Some practices have been implemented along the last decades, particularly those aimed at tailoring the application of fertilizers to the requirements of crops and soil properties, and setting the optimal application schedule. However, research is continuously ongoing in order to reach high efficiency standards through the application of precision agriculture based on big data (Mallarino and Schepers, 2005). Other phosphorus management practices, including the dynamic adaptation of the supply of phosphorus to livestock, the development of intensive crop-livestock integrated systems, and the implementation of phosphorus recovery systems at livestock facilities and greenhouses are still under development and they are not widely deployed in commercial agricultural facilities.

The development and effective implementation of these practices requires computational methods for the assessment, comparison, and selection of techniques. In practice, different computational methods are commonly integrated to assess different dimensions simultaneously. However, criteria often conflict each other, leading to complex decision-making processes managing large amounts of information of conflicting nature. Moreover, the study of the agricultural sector involves the integration of the geographical aspect, since many parameters have a geographic component (becoming geospatial data) to determine the eutrophication vulnerability level at each location, find relationships between human activities and environmental damages, measure the nutrient pollution mitigation performance of different phosphorus management practices at a certain location, etc. As a result, the development of multi-dimensional assessment frameworks evaluating environmental, technical, and economic criteria, as well as the geographical component of the agricultural systems within multi-criteria decision analysis (MCDA) models are powerful tools for assessing and selecting the most suitable phosphorus management technique for each particular case studied, providing solutions tailored to the particular context of each activity. There exist a variety of MCDA methods that can be applied to the nutrient pollution problem. These can be divided into multi-objective decision analysis (MODA) and multi-attribute decision analysis (MADA) methods. MODA methods are used when it exists an infinite number of solutions, and are based on multi-objective optimization models, where multiple conflicting criteria are combined in an objective function. MADA methods are used for discrete choice problems, where the number of feasible solutions is finite. There exist a large number of MADA methods, such as the indicator-based methods, also known as multi-attribute value theory (MAVT) methods used by Martín-Hernández et al. (2021), which is described in Section 2.1. For more informaiton about suitable MCDA methods for addressing the nutrient pollution problem, we refer the reader to Giove et al. (2009).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

EM-H, MT, and MM conceived the ideas, wrote, edited, and reviewed the manuscript.

Funding

The authors acknowledge the funding received from the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant no. 778168, and the funding from Junta de Castilla y León, Spain, under grants EDU/556/2019 and EDU/601/2020.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Arnold, J. G., Srinivasan, R., Muttiah, R. S., and Williams, J. R. (1998). Large area hydrologic modeling and assessment Part I: Model development. *J. Am. Water Resour. Assoc.* 34 (1), 73–89. doi:10.1111/j.1752-1688.1998.tb05961.x

Ashley, K., Cordell, D., and Mavinic, D. (2011). A brief history of phosphorus: From the philosopher's stone to nutrient recovery and reuse. *Chemosphere* 84 (6), 737–746. doi:10.1016/j.chemosphere.2011.03.001

Australian Meat Processor Corporation (2018). "Struvite or traditional chemical phosphorus precipitation – what option rocks?" in *Tech. rep.* (North Sydney, Australia: Australian Meat Processor Corporation).

Baligar, V., Fageria, N., and He, Z. (2001). Nutrient use efficiency in plants. *Commun. soil Sci. plant analysis* 32 (7-8), 921–950. doi:10.1081/css-100104098

Basso, B., Bertocco, M., Sartori, L., and Martin, E. C.2 (2007). Analyzing the effects of climate variability on spatial pattern of yield in a maize-wheat-soybean rotation. *Eur. J. Agron.* 26, 82–91. doi:10.1016/j.eja.2006.08.008

Basso, B., Cammarano, D., Chen, D., Cafiero, G., Amato, M., Bitella, G., et al.8 (2009). Landscape position and precipitation effects on spatial variability of wheat yield and grain protein in Southern Italy. *J. Agron. Crop Sci.* 195, 301–312. doi:10.1111/j.1439-037x.2008.00351.x

Belton, V., and Stewart, T. (2002). *Multiple criteria decision analysis: An integrated approach*. Berlin, Germany: Springer Science & Business Media.

Bouwman, A. F., Beusen, A. H., and Billen, G. (2009). Human alteration of the global nitrogen and phosphorus soil balances for the period 1970-2050. *Glob. Biogeochem. Cycles* 23 (4), a–n. doi:10.1029/2009gb003576

Bouwman, L., Goldewijk, K. K., Van Der Hoek, K. W., Beusen, A. H., Van Vuuren, D. P., Willems, J., et al. (2013). Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period. *Proc. Natl. Acad. Sci. U.S.A.* 110 (52), 20882–20887. doi:10.1073/pnas.1012878108

Carberry, P. S., Muchow, R. C., McCown, R. L., and 5 (1989). Testing the ceres-maize simulation model in a semi-arid tropical environment. *Field Crops Res.* 20, 297–315. doi:10.1016/0378-4290(89)90072-5

Çelen, I., Buchanan, J. R., Burns, R. T., Bruce Robinson, R. B., and Raj Raman, D. R. (2007). Using a chemical equilibrium model to predict amendments required to precipitate phosphorus as struvite in liquid swine manure. *Water Res.* 41 (8), 1689–1696. doi:10.1016/j.watres.2007.01.018

Cerosaletti, P. E., Fox, D. G., and Chase, L. E. (2004). Phosphorus reduction through precision feeding of dairy cattle. *J. Dairy Sci.* 87, 2314–2323. doi:10.3168/jds.S0022-0302(04)70053-3

Chi, Y., Yang, P., Ren, S., and Yang, J.8 (2020). Finding the optimal fertilizer type and rate to balance yield and soil GHG emissions under reclaimed water irrigation. *Sci. Total Environ.* 729, 138954. doi:10.1016/j.scitotenv.2020.138954

Cisternas, I., Velásquez, I., Caro, A., and Rodríguez, A. (2020). Systematic literature review of implementations of precision agriculture. *Comput. Electron. Agric.* 176, 105626. doi:10.1016/j.compag.2020.105626

Cordell, D., Drangert, J.-O., and White, S. (2009). The story of phosphorus: Global food security and food for thought. *Glob. Environ. change* 19 (2), 292–305. doi:10.1016/j.gloenvcha.2008.10.009

Cordell, D. (2010). *The story of phosphorus: Sustainability implications of global phosphorus scarcity for food security*. Ph.D. thesis (Linköping, Sweden: Linköping University).

Council, N. R. (2000). *Nutrient requirements of beef cattle*. Washington, D.C., USA: National Academies Press.

Council, N. R. (2001). *Nutrient requirements of dairy cattle: 2001*. Washington, D.C., USA: National Academies Press.

Doyle, J. D., and Parsons, S. A. (2002). Struvite formation, control and recovery. *Water Res.* 36 (16), 3925–3940. doi:10.1016/s0043-1354(02)00126-4

Ehbrecht, A., Schönauer, S., Fuderer, T., and Schuhmann, R. (2011). P-Recovery from sewage by seeded crystallisation in a pilot plant in batch mode technology. *Water Sci. Technol.* 63 (2), 339–344. doi:10.2166/wst.2011.061

Ellen Mac Arthur Foundation (2017). Food and the circular economy. Available at: https://archive.ellenmacarthurfoundation.org/explore/food-cities-the-circular-economy (Accessed June 13, 2022).

Giove, S., Brancia, A., Satterstrom, F. K., and Linkov, I. (2009). "Decision support systems and environment: Role of mcda," in *Decision support systems for risk-based management of contaminated sites* (Berlin, Germany: Springer), 1–21. doi:10.1007/978-0-387-09722-0_3

Hoagland, P., and Scatasta, S. (2006). "The economic effects of harmful algal blooms," in *Ecology of harmful algae* (Berlin, Germany: Springer), 391–402.

Hu, Y., Sampat, A. M., Ruiz-Mercado, G. J., and Zavala, V. M. (2019). Logistics network management of livestock waste for spatiotemporal control of nutrient pollution in water bodies. *ACS Sustain. Chem. Eng.* 7 (22), 18359–18374. doi:10.1021/acssuschemeng.9b03920

Hu, Y., Zavala, V. M., and Ruiz-Mercado, G. J. (2020). "Advanced decision making and management (ADAM)," in *Tech. rep* (Washington, D.C., USA: US Environmental Protection Agency).

International Fertilizer Industry Association (2007). "Fertilizer best management practices. General principles, strategy for their adoption and voluntary initiatives vs regulations," in *Tech. rep.* (Paris, France: International Fertilizer Industry Association).

Jacobs, B., Cordell, D., Chin, J., and Rowe, H. (2017). Towards phosphorus sustainability in North America: A model for transformational change. *Environ. Sci. Policy* 77, 151–159. doi:10.1016/j.envsci.2017.08.009

Kim, D.-K., Kaluskar, S., Mugalingam, S., Blukacz-Richards, A., Long, T., Morley, A., et al. (2017). A bayesian approach for estimating phosphorus export and delivery rates with the spatially referenced regression on watershed attributes (sparrow) model. *Ecol. Inf.* 37, 77–91. doi:10.1016/j.ecoinf.2016.12.003

Knowlton, K. F., Radcliffe, J. S., Novak, C. L., and Emmerson, D. A.1 (2004). Animal management to reduce phosphorus losses to the environment1. *J. Animal Sci.* 82, E173–E195. doi:10.2527/2004.8213_supple173x

Le Corre, K. S., Valsami-Jones, E., Hobbs, P., and Parsons, S. A. (2009). Phosphorus recovery from wastewater by struvite crystallization: A review. *Crit. Rev. Environ. Sci. Technol.* 39 (6), 433–477. doi:10.1080/10643380701640573

Mallarino, A. P., and Schepers, J. S. (2005). *Role of precision agriculture in phosphorus management practices*. Hoboken, NJ, USA: John Wiley & Sons, 881–908. Ch. 27.

Martín-Hernández, E., Hu, Y., Zavala, V. M., Martín, M., and Ruiz-Mercado, G. J. (2022). Analysis of incentive policies for phosphorus recovery at livestock facilities in the great lakes area. *Resour. Conservation Recycl.* 177, 105973. doi:10.1016/j.resconrec.2021.105973

Martín-Hernández, E., Martín, M., and Ruiz-Mercado, G. J. (2021). A geospatial environmental and techno-economic framework for sustainable phosphorus management at livestock facilities. *Resour. Conservation Recycl.* 175, 105843. doi:10.1016/j.resconrec.2021.105843

Martín-Hernández, E., Ruiz-Mercado, G. J., and Martín, M. (2020). Model-driven spatial evaluation of nutrient recovery from livestock leachate for struvite production. *J. Environ. Manag.* 271, 110967. doi:10.1016/j.jenvman.2020.110967

Mayorga, E., Seitzinger, S. P., Harrison, J. A., Dumont, E., Beusen, A. H., Bouwman, A., et al. (2010). Global nutrient export from watersheds 2 (news 2): Model development and implementation. *Environ. Model. Softw.* 25 (7), 837–853. doi:10.1016/j.envsoft.2010.01.007

Munford, A. G. (1996). The use of iterative linear programming in practical applications of animal diet formulation. *Math. Comput. Simul.* 42, 255–261. doi:10.1016/0378-4754(95)00115-8

Ontario Ministry of Agriculture, Food and Rural Affairs (2021). Greenhouse nutrient feedwater regulation. Available at: http://www.omafra.gov.on.ca/english/nm/regs/gnfpro/gnfreg.htm (Accessed 03June, 2022).

Peyraud, J. L., Taboada, M., and Delaby, L. (2014). Integrated crop and livestock systems in western europe and south America: A review. *Eur. J. Agron.* 57, 31–42. doi:10.1016/j.eja.2014.02.005

Probe, Pollution (2022). "Mapping phosphorus flows in the ontario economy. Exploring nutrient recovery and reuse opportunites in a provincial context," in *Tech. rep.* (Toronto, ON: Pollution Probe).

Reddy, P. P. (2016). "Integrated crop-livestock farming systems," in *Sustainable intensification of crop production* (Berlin, Germany: Springer), 357–370. doi:10.1007/978-981-10-2702-4_23

Salton, J. C., Mercante, F. M., Tomazi, M., Zanatta, J. A., Concenço, G., Silva, W. M., et al. (2014). Integrated crop-livestock system in tropical Brazil: Toward a sustainable production system. *Agric. Ecosyst. Environ.* 190, 70–79. doi:10.1016/j.agee.2013.09.023

Sampat, A. M., Martin, E., Martin, M., and Zavala, V. M. (2017). Optimization formulations for multi-product supply chain networks. *Comput. Chem. Eng.* 104, 296–310. doi:10.1016/j.compchemeng.2017.04.021

Sekaran, U., Lai, L., Ussiri, D. A., Kumar, S., Clay, S., and 9 (2021). Role of integrated crop-livestock systems in improving agriculture production and addressing food security - a review. *J. Agric. Food Res.* 5, 100190. doi:10.1016/j.jafr.2021.100190

Sharpley, A. N. (1990). Epic-erosion/productivity impact calculator: 1, model documentation. *USDA Techn. Bull.* 1759, 235.

Smith, R. A., Schwarz, G. E., and Alexander, R. B. (1997). Regional interpretation of water-quality monitoring data. *Water Resour. Res.* 33 (12), 2781–2798. doi:10.1029/97wr02171

Sulc, R. M., and Franzluebbers, A. J. (2014). Exploring integrated crop-livestock systems in different ecoregions of the United States. *Eur. J. Agron.* 57, 21–30. doi:10.1016/j.eja.2013.10.007

Taifouris, M., and Martin, M.10 (2021). Toward a circular economy approach for integrated intensive livestock and cropping systems. *ACS Sustain. Chem. Eng.* 9, 13471–13479. doi:10.1021/acssuschemeng.1c04014

Tao, W., Fattah, K. P., and Huchzermeier, M. P. (2016). Struvite recovery from anaerobically digested dairy manure: A review of application potential and hindrances. *J. Environ. Manag.* 169, 46–57. doi:10.1016/j.jenvman.2015.12.006

U.S. Department of Agriculture (2011). Animal feeding operations (AFO) and concentrated animal feeding operations (CAFO). Available at: https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/plantsanimals/livestock/afo/(Accessed 03June, 2022).

Vaneeckhaute, C., Belia, E., Meers, E., Tack, F. M., and Vanrolleghem, P. A. (2018). Nutrient recovery from digested waste: Towards a generic roadmap for setting up an optimal treatment train. *Waste Manag.* 78, 385–392. doi:10.1016/j.wasman.2018.05.047