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REPORT

Economic Feasibility Study for Phosphorus Recovery Processes

María Molinos-Senante, Francesc Hernández-Sancho, Ramón Sala-Garrido, Manel Garrido-Baserba

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Abstract Phosphorus recovery from wastewater has become a necessity for sustainable development because phosphorus is a non-renewable essential resource, and its discharge into the environment causes serious negative impacts. There are no economic incentives for the implementation of phosphorus recovery technologies because the selling price of rock phosphate is lower than phosphorus recovered from sewage. The methodologies used to determine the feasibility of such projects are usually focused on internal costs without considering environmental externalities. This article shows a methodology to assess the economic feasibility of wastewater phosphorus recovery projects that takes into account internal and external impacts. The shadow price of phosphorus is estimated using the directional distance function to measure the environmental benefits obtained by preventing the discharge of phosphorus into the environment. The economic feasibility analysis taking into account the environmental benefits shows that the phosphorus recovery is viable not only from sustainable development but also from an economic point of view.

Keywords Cost–benefit analysis · Economic feasibility · Environmental benefits · Phosphorus recovery · Shadow prices · Sustainable development

INTRODUCTION

Phosphorus is a non-renewable resource that is crucial for the development of life and agricultural production. Furthermore, in the nature, there is no substitute for this nutrient (USGS 2005).

According to the study by EcoSanRes (2005), the annual consumption of P_2O_5 in 2050 will be 70 million tons, and at this rate of consumption, half of the current economically viable phosphorus reserves will be consumed within 60–70 years. Other estimates (Steen 1998; Florida Institute of Phosphate Research 1999; Jasinki et al. 1999) offer similar predictions.

Taking into account the scarcity of this resource, phosphorus recovery from wastewater and sewage sludge is becoming necessary for sustainable development. Moreover, the recovery of this nutrient also supposes improvements in the environment and in the operation of wastewater treatment plants (WWTPs). At the same time, it reduces the concentration of this element in sludge, which makes it more useful for agricultural use because the permissible rate of sludge application may be limited by phosphorus content (Köhler 2004).

In this sense, the need to remove phosphorus from wastewater has increased throughout Europe because of the application of Directive 91/271/ECC, especially when the effluent is dumped in areas identified as sensitive to eutrophication. This is because phosphorus is considered to be one of the limiting nutrients in most lakes, reservoirs, and rivers.

There are various methods for phosphorus recovery. However, there is only a limited experience in industrial-scale implementation, some examples of which are shown in the article by Cornel and Schaum (2009). One of the most promising products for phosphorus recovery in the wastewater sector is ammonium magnesium phosphate (struvite or MAP). This mineral shows favorable reaction properties in WWTPs; it reduces the chemical costs of wastewater treatment as it reduces sludge generation. This means that less landfill area is required for sludge disposal. Moreover, struvite is a valuable agricultural fertilizer (Römer 2006; Shu et al. 2006; Martí et al. 2010). In this sense, research (Bridger et al. 1962; Lunt et al. 1964, among others) suggests struvite can be used as a slow release fertilizer at high application rates without the danger of damaging plant roots. Likewise, because struvite is insoluble in natural water, eutrophication problems and infiltration in groundwater are prevented, which represents another advantage in its use as fertilizer. Therefore, phosphorus recovery as struvite can be seen as a basic process for achieving sustainable development.

The recovery of phosphate (and other nutrients) from wastewater and sewage sludge also requires technical and financial efforts (Dockhorn 2009). While the technical feasibility of phosphorus recovery processes from wastewater has been widely studied (Shimamura et al. 2003; de-Bashan and Bashan 2004; Elliott and O'Connor 2007; Pastor 2008; Yen et al. 2010, among others), contributions in the field of economic feasibility are much more limited (Paul et al. 2001; Jeanmaire and Evans 2001; Shu et al. 2006; Berg et al. 2006; Dockhorn 2009, among others).

The costs of recovering phosphate during wastewater treatment can be calculated at 2 € per kg P as a minimum and may total more than 8 € per kg P under specific conditions (Dockhorn 2007; Schaum 2007). Rock phosphate in the United States is sold at between $35 and $50 per ton (The US Geological Survey home page) depending on the purity. These values show that there are no economic incentive for implementing phosphorus recovery technologies in the wastewater sector since it is cheaper for the fertilizer industry to continue using rock phosphate as feedstock.

However, it is important to remember that the recovery of phosphorus from wastewater involves important environmental benefits because it prevents eutrophication in the receiving environment, and increases the availability of a non-renewable resource. In the light of this, when the economic feasibility of projects with environmental effects is analyzed, the internal impacts should be considered; as well as environmental benefits (Hernández et al. 2006). It is important to highlight that internal impacts are those directly linked with the project and can be calculated directly in monetary units because they are regulated by the market. On the other hand, environmental benefits are what in economic terms are known as positive externalities, i.e., benefits that occur when the actions of firms and individuals have an effect on people other than themselves without economic compensation. Unlike internal impacts and, due to the absence of market prices, economic valuation methods are needed for the quantification of externalities.

In this context and from the pioneering study by Färe et al. (1993), and successive developments (Färe and Grosskopf 1998; Färe et al. 2001, 2005, 2006) in the framework of efficiency studies, a stream of research has been produced, which provides a valuation methodology for undesirable outputs. Using the concept of directional distance function, a shadow price is calculated for those goods arising from human and productive activities that have no market value and substantial environmental impacts.

The calculated shadow prices represent the value of externalities that could produce environmental damage if inadequately managed (Hernández et al. 2010). We consider water treatment as a productive process, and we assume that if the phosphorus is not removed from wastewater, then its discharge causes a negative environmental impact on the receiving area. Therefore, phosphorus is an undesirable output derived from the wastewater treatment process, and the calculation of its shadow price provides a proxy for the environmental benefit derived from the recovery of this nutrient.

Despite environmental benefits arising to prevent the discharge of this element into water bodies, conventional methodologies for assessing economic feasibility of phosphorus recovery projects are focus on internal impacts, while external effects are relegated to a series of statements about the advantages, but without any monetary quantification. As a result, the true benefits and costs of many projects are not properly evaluated.

Against this background and in order to assess the real feasibility of phosphorus recovery projects, this study shows a methodology where internal and external impacts are considered. Through an empirical application, a quantification is given of the monetary value of the environmental benefits arising from phosphorus recovery. The methodological approach proposed by Färe et al. (2006) is used in this article for a sample of 20 WWTPs located in the Valencia region (on the Mediterranean coast of Spain), which discharge their effluents into areas with eutrophication problems. The results are useful for determining the best cases in which WWTPs can be found for the economically feasible recovery of phosphorus.

METHODOLOGY

An economic feasibility study of phosphorus recovery is made using a conventional economic analysis methodology, namely, cost–benefit analysis (CBA). The net profit is the difference between benefits and costs (see Eq. 1).

$$\mathrm{NP} = B_{\mathrm{I}} + B_{\mathrm{E}} \quad (1)$$

where NP is the net profit (total income − total costs); B_{I} is the internal benefit (internal income − internal costs); and B_{E} is the external benefit (positive externalities − negative externalities). CBA starts from the premise that a project is only economically feasible if all benefits exceed the aggregate costs, i.e., according to Eq. 1, if the $\mathrm{NP} > 0$.

Internal benefit

In a phosphorus recovery project, internal benefits or internal impacts are those directly linked with the recovery process and can be calculated directly in monetary units because they have market prices. The internal benefit is estimated from the difference between internal income and internal costs. The term internal income includes income earned as a result of the sale of recovered phosphorus, as well as savings from: (i) reduced WWTP operating costs since there is a reduction in reagents needed for the chemical precipitation of phosphorus; (ii) reduced sludge generation, and consequently lower costs associated with its management; and (iii) reduced pipe and tube cleaning because there is less uncontrolled struvite formation.

It is reasonable to assume that a WWTP can recover 1 kg of struvite from 100 m^3 of wastewater (Münch and Barr 2001; van Dijk and Braakensiek 1984). Recovered struvite can be used as a fertilizer because it has similar properties to conventional fertilizers (Taruya et al. 2000; Ahmed et al. 2006; among others). Ueno and Fujii (2001) noted that struvite obtained from wastewater in Japan is being sold to fertilizer companies for €250 per ton, excluding transport costs. Münch and Barr (2001) pointed out after a market study that struvite could be sold in Australia for between €188 and €314 per ton; while Shu et al. (2006) estimated that the market price of struvite was around €464 per ton. More recently, Dockhorn (2009) based on estimations of market fertilizer, estimated the value of struvite at €763 per ton. Therefore, various authors estimate that the market price of struvite is between €188 and €763 per ton.

In relation to the operational cost savings involved in phosphorus recovery compared to conventional removal treatment, Dockhorn (2009) notes that the figure is around 2–3 € per Kg P while Shu et al. (2006) quantified this saving at between 0.79 and 3.92 AUS $ per Kg P.

Internal costs are the result of the sum of investment costs in relation to conventional phosphorus removal treatment. These include civil works (equipment, machinery, and auxiliary facilities); additional operating and maintenance costs (reagents for chemical precipitation and pH value maintenance); and financial costs. In general, costs for phosphorus recovery are strongly influenced by the type of implemented technology. Usually, processing streams at WWTPs primarily extracted from digested sludge dewatering, concentrated effluent, or sewage sludge ash are investigated in regard to their suitability for phosphorus recycling (Maier et al. 2005; Pinnekamp et al. 2005; Lind et al. 2000).

The investment costs depend largely on the size of the WWTP (Hernández and Sala 2009). According to Montag et al. (2009), investment costs for a 100,000 population equivalent (PE) WWTP amount to €3,732,549 and €1,417,739 corresponding to the recovery of phosphorus from the effluent and sludge, respectively, whereas the investment cost for phosphorus recovery from sludge ash totals €11,026,720 for a 15,000 tons $year^{-1}$ incinerator plant.

Operating and maintenance costs depend on the phosphorus concentration in the waste stream to be treated, as well as the reagents used to operate the plant. Berg et al. (2006) estimate that the crystallization process costs for a 45,000 PE plant are between €2.14 and €2.90 PE^{-1} per year. For phosphorus recovery from digested sludge, Dockhorn (2009) estimates operating and maintenance costs for a 350,000 PE plant at €2800 per ton of struvite if the PO_4–P concentration is 50 mg l^{-1}; and €520 per ton if the PO_4–P concentration is 800 mg l^{-1}.

Taking into account these incomes and costs, the internal benefit can be expressed as

$$B_{\mathrm{I}} = \sum_{t=0}^{T} \begin{bmatrix} (\mathrm{APR}_t \times \mathrm{SPP}_t) + (\mathrm{ASR}_t \times \mathrm{CSM}_t) + \\ (\mathrm{ARR}_t \times \mathrm{CR}_t) + (\mathrm{ADR}_t \times \mathrm{CCD}_t) - \\ (\mathrm{IC}_t + \mathrm{OMC}_t + \mathrm{FC}_t) \end{bmatrix} \quad (2)$$

where B_{I} = internal benefit (€); APR = annual volume of phosphorus recovered (kg); SPP_t = present selling price of recovered phosphorus (€ kg^{-1}); ASR = annual volume of reduction of sludge generation (kg); CSM_t = present cost of sludge management (€ kg^{-1}); ARR = annual volume reduction of reagents (kg); CR_t = present cost of reagents (€ kg^{-1}); ADR = annual volume reduction of uncontrolled phosphorus deposit (kg); CCD_t = present cost of cleaning phosphorus deposit (€ kg^{-1}); IC = investment cost (€); OMC_t = present operational and maintenance cost (€); and FC_t = present financial costs (€) and t = year.

All the items considered in Eq. 2 must be expressed in present value. Therefore, on the one hand, for the first four terms (positive ones), it is necessary to apply to each one of them, the discount rate[1] "d" that enables to compensate inflation rate and other risks (see footnote as an example to the selling price of phosphorus). On the other hand, in the last term of this equation (negative one) the discount rate to be applied is "r" where:

$r = d + r_0$

r_0 is free risk rate (basic money remuneration). If $r_0 \geq 0$; $r \geq d$, then, consequently $1/d \leq 1/r$. Thus, it means that $B_{\mathrm{I}} \geq 0$

[1] $\mathrm{SSP}_t = \overline{\mathrm{SSP}}_t * (1 + d)^{-t}$ where: SSP_t = present selling price of recovered phosphorus; $\overline{\mathrm{SSS}}_t$ = nominal selling price of recovered phosphorus; d = discount rate and t = year.

External benefit

Externalities refer to any consequence (positive or negative, intentional, or random) that derives from a project and effects on people without economic compensation. In this sense, phosphorus recovery from waste streams has positive externalities, such as an increase in the availability of a non-renewable resource and important environmental benefits, because if phosphorus discharge is prevented, then its level in water bodies is reduced and, consequently, there are fewer eutrophication problems.

According to Eq. 1, the feasibility analysis of any project requires, in addition to considering the internal benefits, a quantification of the resulting externalities. Thus, the external benefit is given by

$$B_{\mathrm{E}} = \sum_{t=0}^{T} (\mathrm{EP}_t - \mathrm{EN}_t) \tag{3}$$

where B_{E} = present value of external benefit (€); EP = present value of positive externalities (€); EN = present value of negative externalities (€); and t = year.

Like internal benefit, both positive and negative externalities have to be expressed in present value. For this, the discount rate "d" defined in the previous section should be applied to each of the two terms.

While internal benefits can be calculated directly in monetary units, the quantification of external impacts, because of the absence of market prices, requires the use of economic valuation methods. For this reason, the estimation of external impacts is the main obstacle when determining the economic feasibility of a phosphorus recovery project.

As it has been explained previously ("Introduction" section), an alternative method for estimating the environmental benefits derived from wastewater phosphorus recovery projects is by quantifying the shadow price for phosphorus. The phosphorus extracted from wastewater can be considered an undesirable output because it would cause negative impacts if dumped in an uncontrolled manner into the environment, especially in areas sensitive to eutrophication.

The shadow price valuation methodology for undesirable outputs (Färe et al. 2006) is based on the concept of directional distance function. A distance function generalizes the concept of conventional production functions and measures the difference between the outputs produced in the process under study and the outputs of the more efficient process. It is considered that the most efficient process is one that minimizes input consumption and undesirable output generation while maximizing desirable outputs. Denote inputs by $x = (x_1, \ldots, x_N) \in R_+^N$, desirable outputs by $y = (y_1, \ldots, y_M) \in R_+^M$ and undesirable outputs by $b = (b_1, \ldots, b_J) \in R_+^J$. Let $g = (g_y, g_b)$ be a directional vector, and assume $g \neq 0$. The directional output distance function is defined as

$$D_0(x, y, b; g_y, g_b) = \mathrm{Max}\{\beta : (y + \beta g_y, b - \beta g_b) \in P(x)\} \tag{4}$$

The distance function gives the maximum expansion of desirable outputs and the contraction of undesirable outputs that is feasible for the given technology, $P(x)$.

Directional distance function parameterization is carried out in a quadratic form (Chambers 1998) (see Eq. 8). Therefore, unlike the translog function, it may be restricted to satisfy the translation property.

For parameter estimation (α_0, α_n, α_{nn}, β_m, $\beta_{mm'}$, γ_j, γ_{jj}, δ_{nm}, η_{nj}, μ_{mj}) the sum of the distance between the production frontier and individual observations for each period should be minimized (see Eq. 9).

To obtain shadow prices for undesirable outputs, it is necessary to examine the relationship between the maximal revenue function and the directional output distance function. Let $p = (p_1, \ldots, p_M) \in R_+^M$ represent desirable outputs prices and let $q = (q_1, \ldots, q_J) \in R_+^J$ represent undesirable output prices. The revenue function, which accounts for the negative revenue generated by the undesirable outputs, is defined as

$$R(x, p, q) = \mathrm{Max}_{y,b}\{py - qb : (y, b) \in P(x)\} \tag{5}$$

The revenue function, $R(x,p,q)$, gives the largest feasible revenue that can be obtained from inputs, x, when the process faces desirable output prices, p, and undesirable output prices, q.

The deduction of shadow prices for undesirable outputs means assuming that the shadow prices of an absolute desirable output coincide with the market prices. If y is a desirable output whose market price p is equal to its shadow price pm, and if b is each of the undesirable outputs, and q_j is the shadow price of each undesirable, then the absolute shadow prices are given by

$$q_j = -p_m \frac{\partial D_0(x, y, b; g)/\partial b_j}{\partial D_0(x, y, b; g)/\partial y_m} \tag{6}$$

By replacing Eqs. 2 and 3 in the initially proposed General Equation (1), the following expression is obtained:

$$\mathrm{NP} = \sum_{t=0}^{T} \begin{bmatrix} (\mathrm{APR}_t \times \mathrm{SPP}_t) + (\mathrm{ASR}_t \times \mathrm{CSM}_t) + \\ (\mathrm{ARR}_t \times \mathrm{CR}_t) + (\mathrm{ADR}_t \times \mathrm{CCD}_t) - \\ (\mathrm{IC}_t + \mathrm{OMC}_t + \mathrm{FC}_t) + (\mathrm{EP}_t - \mathrm{EN}_t) \end{bmatrix} \tag{7}$$

SAMPLE DATA DESCRIPTION

The study was undertaken in a sample of 20 WWTPs in which there is no removal or recovery of phosphorus, but effluents of which are discharged into areas with eutrophication problems. Under the current conditions of wastewater treatment, phosphorus removal is only associated with the growth of microorganisms. However, to estimate the environmental benefit of recovering phosphorus, it has been assumed that after the implementation of appropriate technologies, the concentration of this nutrient in the effluent would be the determined by Directive 271/91/CEE for sensitive areas, i.e., 2 mg l^{-1} when WWTP capacity is between 10,000 to 100,000 PE and 1 mg l^{-1} if capacity is greater than 100,000 PE.

The plants under study are located in the coastal area of the Valencia region (on the Mediterranean coast of Spain). All the WWTPs use a similar process in which a desirable output (treated water) is obtained together with five undesirable outputs: suspended solids (SS), nitrogen (N), phosphorus (P), and organic matter measured as chemical oxygen demand (COD) and biological oxygen demand (BOD). The inputs needed are energy, staff, waste management, and maintenance. These variables are described in Table 1. The statistical information comes from the Valencian wastewater authority—the *Entitat de Sanejament d'Aigües—EPSAR* (2008).

As previously stated, the quantification of shadow prices for pollutants removed in the treatment process means assuming that the shadow price of the desirable output (reclaimed water) is known and coincides with the market price. The effluent of the WWTPs under study is dumped to wetlands with eutrophication problems. According to Hernández et al. (2010) and based on average values that the Spanish authorities have paid in a number of initiatives performed in the fields of reuse and improving the quality of the environment surrounding reclaimed water, the reference price of treated water is 0.9 € m^{-3}.

Table 1 Sample description

	Mean	Standard deviation	Minimum	Maximum
Inputs (€ m^{-3})				
Energy	0.088	0.054	0.027	0.125
Staff	0.166	0.109	0.053	0.428
Waste management	0.097	0.097	0.004	0.235
Maintenance	0.037	0.024	0.009	0.047
Desirable output (m^3 $year^{-1}$)				
Treated water	1,317,540	1,101,344	400,297	3,267,300
Undesirable outputs (kg m^{-3})				
SS	0.296	0.353	0.151	0.852
N	0.039	0.035	0.009	0.161
P	0.005	0.005	0.002	0.020
COD	0.630	0.415	0.250	1.845
BOD	0.303	0.326	0.041	1.201

RESULTS

The objective function to be minimized (see "Methodology") refers to the 20 units of the sample. To solve the nonlinear problem (Eq. 9), we used GAMS software. The value of parameters is shown in Table 2.

The estimation of the directional distance function enables us to obtain the shadow prices for each removed pollutant during the wastewater regeneration process for each WWTP under study. Given that this study aims to quantify the environmental benefits of phosphorus recovery, we will focus on analyzing the results obtained for this pollutant. The shadow price value, expressed in € kg^{-1} is shown in Table 3. According to the existing literature (Ha et al. 2008; Hernández et al. 2010; Molinos et al. 2010; among others), shadow prices are negative. These shadow prices represent an estimation of the environmental benefits obtained from phosphorus recovery.

Once the phosphorus shadow price in € kg^{-1} is quantified and the amount of phosphorus removed per cubic meter of treated water is known, the monetary value of the environmental benefit in € m^{-3} and € $year^{-1}$ can be obtained directly (Table 3).

According to the results presented in Table 3, the mean value of the phosphorus shadow price is −42.74 € kg^{-1}—meaning that for every kg of phosphorus that is not dumped into the environment, the damage prevented, or the environmental benefit generated equals €42.74. The total environment benefit derived from a phosphorus recovery project varies greatly between the different plants under consideration: the minimum value is 0.006 € m^{-3}, while the maximum is 0.474 € m^{-3}. The weighted average, depending on the volume of treated wastewater, is 0.218 € m^{-3}.

Finally, information about the environmental benefit expressed in € $year^{-1}$ is given. The integration of this value in Eq. 7 enables us to obtain an indicator of the economic feasibility of a proposed phosphorus recovery project, considering not only internal impacts but also externalities.

In this sense and as an example, we assume a WWTP that recovers phosphorus as struvite from digested sludge and whose treatment capacity is 100,000 PE. The annual wastewater volume is 500,000 m^{-3} with a phosphorus concentration in the influent of 9 and 1 mg l^{-1} in the effluent. The amortization period is assumed to be 20 years, interest rate is 6%, and discount rate is 3.5%. On the other hand and, taking into account that both internal costs and benefits quantified and collected in different studies (see "Methodology" section) have a wide range of values, to assess the economic feasibility of this example project, average values have been selected. Likewise, as described in Table 3, the total environment benefit varies greatly between the different WWTPs under study. Therefore, and following the same criteria, it was decided

Table 2 Parameters and coefficients associated with a quadratic function

α_0	46.62861751	γ_{11}	−0.00000005	η_{41}	0.00000003
α_1	0.00883921	γ_{12}	−0.00000001	η_{12}	−0.00000007
α_2	0.00805580	γ_{13}	1.653004E−9	η_{22}	−0.00000003
α_3	0.00000163	γ_{14}	−0.00000037	η_{32}	0.00000002
α_4	0.00718565	γ_{15}	0.00000079	η_{42}	−0.00000008
β_1	−0.00747908	γ_{22}	0.00000006	η_{13}	0.00000011
γ_1	−0.00000954	γ_{23}	−0.00000008	η_{23}	−0.00000005
γ_2	0.00000762	γ_{24}	0.00000049	η_{33}	−0.00000001
γ_3	0.00007105	γ_{25}	−0.00000196	η_{43}	0.00000011
γ_4	0.00090995	γ_{33}	0.00000003	η_{14}	−0.00000075
γ_5	0.99154184	γ_{34}	−0.00000023	η_{24}	0.00000083
α_{11}	−0.00000024	γ_{35}	0.00000159	η_{34}	−0.00000004
α_{12}	−0.00000049	γ_{44}	0.00000341	η_{44}	−0.00000118
α_{13}	0.00000002	γ_{45}	−0.00001855	η_{15}	−0.00000130
α_{14}	0.00000013	γ_{55}	0.00001475	η_{25}	−0.00000410
α_{22}	0.00000002	δ_{11}	0.00000004	η_{35}	0.00000021
α_{23}	−0.00000001	δ_{21}	0.00000007	η_{45}	0.00000615
α_{24}	−0.00000024	δ_{31}	2.126832E−9	μ_{11}	−4.197860E−9
α_{33}	3.128917E−9	δ_{41}	−0.00000004	μ_{12}	0.00000007
α_{34}	6.193698E−9	η_{11}	0.00000025	μ_{13}	−8.382139E−9
α_{44}	−0.00000010	η_{21}	−0.00000002	μ_{14}	0.00000009
β_{11}	−7.257999E−8	η_{31}	−3.66252E−9	μ_{15}	−0.00000022

to use the average shadow price of the 20 WWTPs under study, i.e., 42.74 € kg^{-1} of phosphorus removed.

Table 4 shows that if an economic feasibility study is based on internal benefits, then the recovery of phosphorus is not feasible because a negative value is obtained. However, when the average value of the external benefit is taken into account (Table 3), phosphorus recovery is feasible in economic terms because the result is positive. It is important to note that in the quantification of externalities, only environmental benefits have been estimated, and not the increase in resource availability. This means that if this impact was quantified and incorporated into the economic feasibility analysis, the obtained results would be even more favorable. Based on the obtained results, phosphorus recovery is an economically feasible process as long as the environmental benefits are considered.

CONCLUSIONS

There is a growing interest in phosphorus recycling not just because it is a non-renewable resource, but because the recovery of this nutrient from wastewater also supposes important improvements in the environment and in the operation of WWTPs.

Table 3 Phosphorus shadow price and environmental benefit of its recovery

WWTP	Shadow price (€ Kg^{-1})	Recovery phosphorus (Kg m^{-3})	Wastewater volume (m^3 $year^{-1}$)	Environmental benefit (€ m^{-3})	Environmental benefit (€ $year^{-1}$)
1	−57.245	0.004	1,192,232	0.231	275,047
2	−49.055	0.003	596,472	0.309	184,338
3	−74.019	0.005	1,318,212	0.363	478,107
4	−41.207	0.004	800,195	0.237	189,599
5	−22.940	0.002	520,403	0.116	60,167
6	−51.933	0.020	2,568,842	0.266	684,380
7	−32.784	0.004	780,956	0.195	152,082
8	−41.812	0.015	3,092,992	0.237	733,273
9	−20.873	0.005	769,513	0.006	4751
10	−62.780	0.003	845,995	0.253	214,040
11	−17.880	0.001	1,416,255	0.008	11,142
12	−41.600	0.003	565,956	0.249	140,792
13	−53.628	0.005	1,909,878	0.172	327,756
14	−36.881	0.004	667,136	0.283	188,473
15	−47.073	0.009	1,424,665	0.354	504,321
16	−79.815	0.011	3,267,300	0.310	1,011,819
17	−31.651	0.002	721,243	0.123	89,030
18	−44.269	0.002	569,720	0.174	99,119
19	−61.848	0.002	922,553	0.130	119,823
20	−27.254	0.001	400,297	0.087	34,802
Average	−42.740	0.005	1,317,540	0.218	301,785

Table 4 Costs, benefits, and feasibility estimations

	Mean
Internal costs (€ year^{-1})	
Investment	70,887
Operation and maintenance	14,000
Financial costs	4253
Internal incomes (€ year^{-1})	
Struvite sale	2378
Savings in operation costs	10,000
Internal feasibility (€ year^{-1})	
Internal incomes − Internal costs	−76,762.05
External benefits (€ year^{-1})	
Environmental benefits	170,960
Complete feasibility (€ year^{-1})	
Internal benefits − External benefits	94,198.17

Nowadays, conventional methodologies for assessing economic feasibility of phosphorus recovery projects are focused exclusively on internal impacts while, external effects are relegated to a series of statements about the advantages, but without any monetary quantification. As a result, the true benefits and costs of many projects are not properly evaluated. Therefore, in order to assess the real feasibility of phosphorus recovery projects, this study shows a methodology and an empirical application where both type of impacts are considered and quantified.

The results show that when a phosphorus recovery process is analyzed taking into account just internal impacts, such projects are not economically viable. However, if in addition to these impacts, the environmental benefits of avoiding the discharge of phosphorus are incorporated, then an economic feasibility analysis provides positive results. Therefore, phosphorus recovery is an economically feasible process as long as environmental benefits are considered.

As a general conclusion, we would emphasize that when the economic feasibility of a phosphorus recovery project is assessed, both authorities and WWTP-operating companies must take into account the benefits with market value, not only because the development of such projects can be justified, but also for other reasons, such as an increase in the availability of a non-renewable resource or reduction of environmental impacts, which must be incorporated in the economic feasibility study too.

Finally, we can remark that for any process to be judged as sustainable, it must comply with environmental, socio-cultural, and economic needs. Therefore, the on-going research is focused on incorporating socio-cultural variable to obtain a complete indicator of sustainability for phosphorus recovery process.

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APPENDIX

Given the directional vector $g = (1,1)$ and assuming $k = 1, \ldots, K$ treatment plants operating in a period, the quadratic directional distance function for WWTP k is expressed as

$$\begin{aligned} & D_0(x_k, y_k, b_k; 1, 1) \\ & = \alpha + \sum_{n=1}^{N} \alpha_n x_{nk} + \sum_{m=1}^{M} \beta_m y_{mk} + \sum_{j=1}^{J} \gamma_j b_{jk} \\ & \quad + \frac{1}{2}\sum_{n=1}^{N}\sum_{n'=1}^{N} \alpha_{nn'} x_{nk} + \frac{1}{2}\sum_{m=1}^{M}\sum_{m'=1}^{M} \beta_{mm'} y_m y_{m'} \\ & \quad + \frac{1}{2}\sum_{j=1}^{J}\sum_{j'=1}^{J} \gamma_{jj'} b_j b_{j'} + \sum_{n=1}^{N}\sum_{m=1}^{M} \delta_{nm} x_{nk} y_{mk} \\ & \quad + \sum_{n=1}^{N}\sum_{j=1}^{J} \eta_{nj} x_{nk} b_{jk} + \sum_{m=1}^{M}\sum_{j=1}^{J} \mu_{mj} y_{mk} b_{jk} \end{aligned} \tag{8}$$

Equation 8: Quadratic directional distance function.

$$\begin{aligned} & \mathrm{Min} = \sum_{k=1}^{K} [D_0(x_k, y_k, b_k; 1, 1) - 0] \\ & \text{s.t.}: \\ & \text{(i)} \quad D_0(x_k, y_k, b_k; 1, 1) \geq 0, \quad k = 1, \ldots, K \\ & \text{(ii)} \quad \frac{\partial D_0(x_k, y_k, b_k; 1, 1)}{\partial b_j} \geq 0, \quad j = 1, \ldots, J, \ k = 1, \ldots, K \\ & \text{(iii)} \quad \frac{\partial D_0(x_k, y_k, b_k; 1, 1)}{\partial y_m} \leq 0, \quad m' = 1, \ldots, M, \ k = 1, \ldots, K \\ & \text{(iv)} \quad \frac{\partial D_0(x_k, y_k, b_k; 1, 1)}{\partial x_n} \geq 0, \quad n = 1, \ldots, N, \\ & \text{(v)} \quad \sum_{m=1}^{M} \beta_m - \sum_{j=1}^{J} \gamma_j = -1; \ \sum_{m'=1}^{M} \beta_{mm'} \\ & \qquad - \sum_{j=1}^{J} \mu_{mj} = 0; \ m = 1, \ldots, M; \\ & \qquad \sum_{j'=1}^{J} \gamma_{jj'} - \sum_{m=1}^{M} \mu_{mj} = 0; \ j = 1, \ldots, J; \ \sum_{m=1}^{M} \delta_{nm} \\ & \qquad - \sum_{j=1}^{J} \eta_{nj} = 0; \ n = 1, \ldots, N; \\ & \text{(vi)} \ \alpha_{nn'} = \alpha_{n'n}; \ \beta_{mm'} = \beta_{m'm}; m \neq m', \gamma_{jj'} = \gamma_{j'j}, \ j \neq j' \end{aligned} \tag{9}$$

Equation 9: Nonlinear program to minimize the sum of the distance between the production frontier and individual observations.

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AUTHOR BIOGRAPHIES

María Molinos-Senante (✉) is a Doctoral Candidate at the University of Valencia. Her research interests include environmental economics, especially the economic valuation of environmental benefits derived from wastewater treatment.
Address: Department of Applied Economics II, Faculty of Economics, University of Valencia, Campus dels Tarongers, 46022 Valencia, Spain.
e-mail: Maria.Molinos@uv.es

Francesc Hernández-Sancho is a Professor at the University of Valencia and Director of Water Economics Research Group. His research interests include water economics, especially efficiency aspects and cost modelling.
Address: Department of Applied Economics II, Faculty of Economics, University of Valencia, Campus dels Tarongers, 46022 Valencia, Spain.
e-mail: Francesc.hernandez@uv.es

Ramón Sala-Garrido is a Professor at the University of Valencia. His research interests include optimization processes, especially focus on environmental technologies.
Address: Department of Mathematics for Economics, Faculty of Economics, University of Valencia, Campus dels Tarongers, 46022 Valencia, Spain.
e-mail: Ramon.sala@uv.es

Manel Garrido-Baserba is a Doctoral Candidate at the University of Girona. His research interests include wastewater treatment technologies, especially decision support systems for assessing the optimal technology.
Address: Catalan Institute for Water Research, Scientific and Technological Park, H2O Building, Emili Grahit 101, 17003 Girona, Spain.
e-mail: mgarrido@icra.cat