Nutrients recovery from Treated Secondary Mainstream in an Urban Wastewater Treatment Plant: A financial assessment case study

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Abstract

This study presents the financial assessment for implementing an ammonium and phosphate simultaneous recovery process based on the use of calcium activated synthetic zeolites in a large urban Waste Water Treatment Plant (WWTP) located in the Metropolitan Area of Barcelona.

A calcium activated synthetic zeolites was selected, after a benchmarking analysis, as it reported capability for simultaneously recover ammonium and phosphate by a combined mechanism of ion exchange for ammonium and formation of insoluble mineral phase for phosphate. The loaded sorbent, rich in ammonium and phosphate, can be used as slow-release fertilizer.

Financial indexes such as the net present value, the internal return Rate, the return of investment and the payback period were calculated concluding that the integration of a zeolite-based sorption treatment stage in the main stream is economically feasible, with a reasonable payback period. The need, to achieve low-levels of P and N on the discharged waters and the need to develop more sustainable WWTP facilities indicate that the deployment of nutrient recovery solutions will be encouraged. The sensitivity analysis carried out to define the critical parameters of the economic performance of the technology allows concluding that the main variable in the viability of the nutrient recovery unit is related to the nutrients sorbent, both in the cost of purchase and in the market for the sorbent loaded with nutrients.

Keywords: ammonium: phosphate; wastewater; nutrient recovery; zeolite; economic feasibility

1. Introduction

Nitrogen and phosphorus are essential elements for life and large amounts of these elements, mainly in the form of ammonium and phosphate, are needed for fertilizer production in order to supply growing population food demand (Roberts and Johnston, 2015; Röhling, 2010). It is estimated that about 22 x 10^6 ton/y of phosphorus from mined fossil phosphate resources are added to the world economy (Reijnders, 2014), which leads to a significant alteration of the natural cycle of these elements resulting in problems with air and water quality as well as overall ecosystem balance (Bennett and Schipanski, 2013; Driscoll et al., 2003; Galloway and Cowling, 2002; Groffman and Rosi-Marshall, 2013).

Furthermore, nitrogen and phosphorus discharge limits become increasingly stringent. European Urban Waste Water Treatment Directive set the maximum annual mean total nitrogen concentration between 1.5 and 10 mgN/L depending on the size of the urban area (Oenema et al., 2011) and phosphorus discharge regulation set its concentration on 2 mgP/L in Spain, 1 mgP/L in France, 0.1 mgP/L in UK or 0.01 mgP/L in different states of USA.

In the case of phosphorus, conventional treatments such as chemical precipitation or biological removal are not able to reach concentrations below 0.1 mgP/L and it is necessary to identify technical and economically feasible technologies able to reach ultra-low levels.

Furthermore, urban WWTPs are not any more considered as pollution removal systems but as resources (nutrients and energy) recovery plants (van der Hoek et al., 2016). In this new scheme, the systems focus mainly on the recovery of resources and the reuse of water to promote the circular economy approach where the pollution load becomes a source of secondary raw materials that can be recovered giving an added value to these sources (Kabbe et al., 2017; Ribanova et al., 2017; Scholz, 2017).

The use of secondary raw materials with sorption properties (e.g., natural sorbents or industrial wastes) is an area of increasing interest. Low cost sorbents with high affinity for ammonium and phosphate provide and attractive solution that offers the potential to recover nutrients of high quality that can be directly applied as a fertilizer as most of them will contain (N, P and K) (Egle et al., 2015; Scholz et al., 2013), which contribute to plant growth.

Furthermore, natural sorbent materials are often locally abundant, easy to dispose and include environmental friendly by-products such as shellfish shells (Abeynaike et al., 2011; Xiong et al., 2011), fly ash (He et al., 2012) or slag (Barca et al., 2012; Haddad et al., 2015; Jaouadi et al., 2014).

A summary of currently available phosphate and ammonium single recovery technologies from treated secondary effluent are listed in Table S1, most of them are already implemented in large WWTPs while in other cases has been applied to small scale (e.g., household in isolated communities).

Four technologies were identified, among all options listed in Table S1, with a TRL greater than 8 (the system was completed and qualified through test and demonstration (United States Department of Defense, 2011)), which can produce effluents with ultra-low phosphorus (0.05 mgP/L) concentration: Polonite, PhosphoReduc, CoMag and BluePro.

After the critical review of the state of the art, it can be concluded that there are several technologies available for the recovery of phosphorus from the WWTPs, but there is a lack of solutions focused on the recovery of nitrogen, since it is not a resource that presents scarcity, as if it exists for phosphorus. Different initiatives are widely developed worldwide to recover P for fertilization application from wastes generated on WWTPs. All of them are centered in two main directions: a) recovery of P as struvite from the sludge anaerobic digestion side-streams and b) recovery of P as phosphoric acid from the mono-incineration ashes generated from thermal treatments of sewage sludge in most of the northern countries of Europe and Japan (Amann et al., 2018). However, any initiative to recover ammonium at full scale could be found and the need to promote the deployment of solutions is a real challenge for the next decade.

In view of that, the aim of this study is to assess the financial feasibility of implementing a nutrients (simultaneous phosphorus and nitrogen) recovery system based on sorption technology from WWTP treated secondary effluent considering the CAPEX and OPEX of the required facilities, and potential revenues from cost savings and the sale of loaded adsorbent. The evaluation will be performed in a scenario in which the following boundary conditions have been selected: i) the use of a sorbent with dual capacity to sorb N and P simultaneously; ii) the implementation to a large WWTP (treatment capacity > $3m^3/s$) that incorporates a tertiary treatment; and iii) the saturated sorbent enriched on N, P will be commercialized as fertilizer.

2. Methodology

2.1 Ammonia and phosphate adsorbents selection

In previous studies the evaluation of polymeric sorbents as well as different salt activated synthetic zeolites for nutrients recovery at the lab scale have been performed. The sorption performance of these sorbents is summarized in table 2, where $t_{90\%}$ is the time required for reaching the 90% of maximum sorption capacity.

Table 2: Equilibrium and kinetic sorption properties of assessed adsorbents at lab scale

	q_N [mg N/g)^1	q_P [mg P/g]^2	$t_{90\%}$ [min]^3	Reference
FO36	-	29.1	65	(You et al., 2016b)
Fiban-As	-	52.9	50	(You et al., 2016a)
Ze-Na	13.2	-	10	(You et al., 2017b)
Ze-K	22.6	-	2	(You et al., 2017a)
Ze-Ca	95.7	38.8	30	
Ze-Mg1	42.9	10.5	20	
Ze-Mg2	47.1	7.8	-	

1: qN [mg N/g) is the total sorption capacity for ammonium; 2: qP [mg P/g] is the total sorption capacity for ammonium; and 3: t90% is the time required for reaching the 90% of maximum adsorption capacity.

The synthetic zeolite Ze-Ca was selected for the present study as it reported the best performance for simultaneous recovery of nitrogen and phosphorus from wastewater treated effluent in terms of the sorption capacity for both nutrients and the kinetic parameters that showed a faster sorption rate, which represents a short hydraulic retention time (HRT). In addition, tertiary reactive media filtration proved to be one of the most cost effectiveness alternatives for phosphorus removal in municipal wastewater treatment (Bashar et al., 2018).

Furthermore, it is considered the Baix Llobregat WWTP as it is the largest and newest WWTP in the Metropolitan Area of Barcelona, which includes a water regeneration station, built in 2007 and which is based on filtration and reverse osmosis. This facility could be used for the filtration (ultrafiltration (UF) unit) and separation of loaded zeolite from treated secondary effluent (Hermassi et al., 2016).

2.2 The Baix Llobregat WWTP (BLl-WWTP) as nutrients recovery site study

The BLl-WWTP began to work at 2002 and several improvements have been introduced since then, such as the biologic treatment of wastewater, anaerobic digestion of sewage sludge or the implementation of a water regeneration station.

Nowadays, this plant treats the 36% of the wastewater generated in the Metropolitan Area of Barcelona and it provides service to approximately 2 million of population equivalent (PE) by treating 273330 m^3/d of wastewater, which represents 65% of its design flow (4.86 m^3/s) (Àrea Metropolitana de Barcelona, 2017a). According to the average composition of the wastewaters influent values (60 gN/m^3 and 6.8 gP/m^3), the amount of N and P reaching the WWTP approaches to 9200 ton/y and 1100 ton/y, respectively.

12 identical working lines consisting on a primary settlement and a conventional secondary biological treatment compose the BLl-WWTP. At the initial design, the main part of the treated effluent was discharged into the Mediterranean Sea through an emissary 3.2 km long (Köck-Schulmeyer et al., 2011).

However, due to water crisis, a regeneration station was installed in 2007 with the capacity to provide tertiary treatment to WWTP effluent for reuse in agricultural irrigation, wetland conservation, groundwater hydraulic barriers against marine saline intrusion, and groundwater recharge of Llobregat river aquifer. The tertiary treatment consists on ultrafiltration (UF), reverse osmosis (RO), reverse electrodialysis (EDR) and disinfection (Köck-Schulmeyer et al., 2011). Analysis of the average composition of the treated water along 2012 indicates that approximately 1200 tonN/y and 390 tonP/y were discharged into the Mediterranean Sea.

The scheme of the BLI-WWTP and the main stages of treatment are shown in Figure 1. The zeolite filtration system is proposed to be installed after the secondary clarifier to use the existing UF unit of the regeneration station for separating the loaded zeolite from the treated water as has been proved successfully elsewhere (Hermassi et al., 2016).

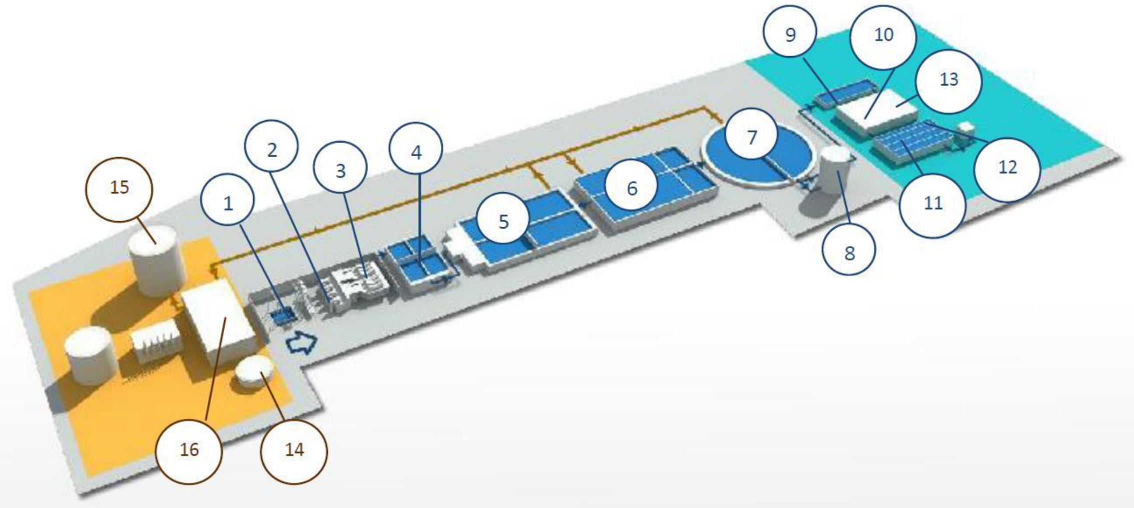
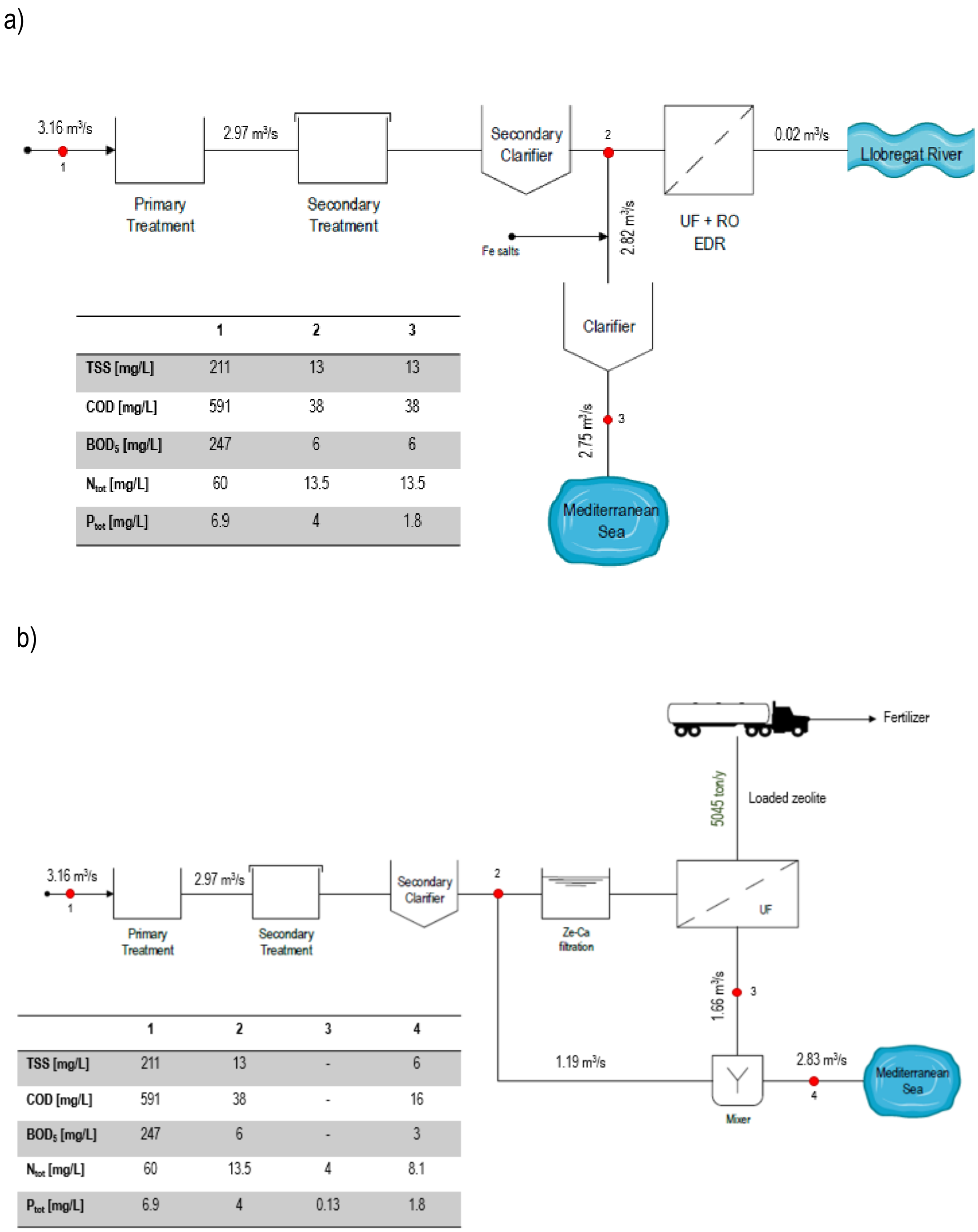


Figure 1: Scheme of the BLI-WWTP configuration (Àrea Metropolitana de Barcelona, 2017b): 1 Sedimentation tank, 2 Pumps, 3 Bar screen, 4 Grit chamber, 5 Primary clarifier, 6 Biologic reactor, 7 Secondary clarifier, 8 Treated water discharge, 9 Flocculation tank, 10 Lamella clarifier, 11 Screening, 12 Disinfection, 13 UF and RO+EDR, 14 Sludge thickener, 15 Sludge Digester, 16 Sludge thermic dewatering

The current phosphorus removal scheme in BLI-WWTP (Figure 2a) and the proposed scheme for nutrients recovery (Figure 2b) are depicted in Figure 2. The flow distribution shown in Figure 2b is defined in order to obtain a final P concentration below 2 mgP/L, as established by EU regulation (Mas-Pla et al., 2006).



a)

	1	2	3
TSS [mg/L]	211	13	13
COD [mg/L]	591	38	38
BOD_5 [mg/L]	247	6	6
N_{tot} [mg/L]	60	13.5	13.5
P_{tot} [mg/L]	6.9	4	1.8

b)

	1	2	3	4
TSS [mg/L]	211	13	-	6
COD [mg/L]	591	38	-	16
BOD_5 [mg/L]	247	6	-	3
N_{tot} [mg/L]	60	13.5	4	8.1
P_{tot} [mg/L]	6.9	4	0.13	1.8

Figure 2: a) Current and b) proposed working scheme and sampling data for recovery of nutrients at the BLI-WWTP. Flow-rates and composition of the main parameters have been provided by the Metropolitan Area of Barcelona (Àrea Metropolitana de Barcelona, 2017a).

It is worth mentioning that the average wastewater sampling data shown in Figure 2 are from 2010, however, the BLI-WWTP has not introduced any significant technical modifications since then;

therefore, the average composition of the initial and treated wastewater has not presented relevant changes and can be used for this analysis. However, BLI-WWTP total treated flow is updated to the latest available records (2015).

2.3. Financial Assessment

Financial ratios were used in this work for assessing the economic feasibility of implementing a nutrients recovery unit based on zeolite sorbents in the BLI-WWTP. The net present value (NPV), internal rate of return (IRR), return of investment (ROI) and payback period (PP) were estimated for this purpose.

Net Present Value (NPV) (Eq. 1) is expressed as the difference between the current value of cash of inflows and outflows over a period and it is used to analyze the profitability of any investment.

$$NPV = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+r)^t} - I_0 \qquad \text{Eq. 1}$$

where B_t and C_t are the inflows and outflows at the period t, r is the discount rate, and I_0 is the investment at t=0.

Internal Rate of Return (IRR) is calculated by solving the Eq. 2 and it specifies whether the project breaks even with an NPV of zero; if the obtained result is greater than the discount rate, the project is feasible.

$$0 = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+IRR)^t} - I_0 \qquad \text{Eq. 2}$$

Return of Investment (ROI) (Eq. 3) is a measure to evaluate the efficiency of an investment, since it measures the amount of return of an investment in relation to the cost of investment.

$$\mathrm{ROI} = \frac{\text{Gain from investment} - \text{Cost of investment}}{\text{Cost of investment}} \mathrm{x}100 \qquad \text{Eq. 3}$$

The Payback Period (PP) (Eq. 4) is the time required to recover the cost of the investment. For ROI calculation, a lifetime of 20 years has been considered taking as a reference the values reported for gravity filtration units in WWTPs (Machado et al., 2007)

$$\mathrm{PP} = \frac{\text{Cost of investment}}{\text{Annual Gain from investment}} \qquad \text{Eq. 4}$$

The investment is required for the installation of zeolite filtration tanks, as well as for the pumping systems and the modification of the plant pipelines. No further investment is needed as the zeolite filtration/separation (Alkas et al., 2013; Foreman, 1985; Hansen, 1997) will be performed by integration of the existing UF modules in the tertiary treatment stage of the regeneration station.

For zeolite filtration tank dimensioning it was considered the BLI-WWTP maximum treatment flow, the volume of zeolite for targeting a phosphorus concentration of 0.05 mg/L and the volume of wastewater for 60 minutes of HRT by using a scaling factor of 2 to the kinetic parameter obtained at the laboratory scale (Table 2). Taking into account these criteria it was determined that the volume needed for the filtration tanks was 860 m^3.

The OPEX were calculated considering the cost of sorbent as well as an increase 5% of the current BLI-WWTP OPEX (8.4 M €/year) due to the significant increase of operational demand of UF modules in terms of energy and maintenance. Moreover, taking into account a lifetime of the UF membrane of 10 years, an annual amortization of 10% of total cost of UF modules was considered (2.9 M €) composed of hollow fiber UF membranes with a total active surface of 288000 m^2 able to obtaining a filtration flow up to 2 m^3/s (Originblue, 2017).

Finally, as the loaded zeolite contains calcium phosphate (You et al., 2017a) it can be sell as Triple SuperPhosphate (TSP) fertilizer with approximately a 15% of phosphorus nutrient content. According to Maaß, (2014) the commodity price for fertilizer which contains 20% of phosphorus nutrient is set on 220 €/ton. In addition, the implementation of the zeolite filtration system would lead to a saving in the costs related to the iron salt used as coagulant to limit the phosphorus levels in the discharge water according to the current regulation. According to a non-published study performed by SUEZ Spain, the average cost of the phosphorus chemical removal is estimated on 0.7 €/kg P_{in}.

3. Results and Discussion

3.1. Financial Assessment

For the estimation of CAPEX, the cost reported by Saiz (2010) was taken as a reference for a 1000 m^3 tank resulting in 250.6 k€ at 2010. Thus, considering a linear decrease of the cost with the tank volume and a Retail Price Index (RPI) increase of 11.6 % (Instituto Nacional de Estadística, 2017) from 2010 to December 2017, the investment for each sedimentation tank can be estimated on 239 k€. For achieving 1.8 mgP/L of total phosphorus concentration at the discharged wastewater stream, the installation of zeolite filtration tank is needed in 7 operating lines, which leads to a cost of 1673 k€.

Furthermore, according to the project for reusing BLI-WWT treated water quotation for the BLI-WWTP regeneration station, pumping facilities and pipeline installations would cost around 150 k€ (Depuradora Baix Llobregat S.A., 2007), which represents a total initial investment of 1823 k€.

Wastewater production in Metropolitan Area of Barcelona have been quite constant with a fluctuation of ±1% in the last 3 years, thus, for the financial assessment during BLI-WWTP lifetime, an annual increase of treated flow of 1%, a sorbent cost of 115 €/ton and the UF membrane price of 10 $€/m^2$ were considered. Finally, a discount rate of 4% was considered, as it was the mean value in Euro Area since year 2000 for reliable business (Federal Reserve Bank of St. Louis, 2018). A summary of variables considered for the economic analysis is listed in the Table 3.

Table 3: Summary of considered variables for economic assessment

BLI-WWTP lifetime	**20 years**	**Raw zeolite price**	**115 €/ton**
P_{tot} after zeolite filtration	0.01 mgP/L	Loaded zeolite (15% of PO_4^{3-} content)	220 €/ton

P_{tot} final	1.8 mgP/L	Chemical cost saving	0.7 €/kg P_{in}
HRT	60 minutes	UF membranes	288000 m^2
Variation of BLI-WWTP treated flow	+ 1% per year	UF membranes price	10 €/m^2
Discount rate	4%		

The expected evolution of NPV (according to Eq. 1 - 4) is exhibited in Figure 3.

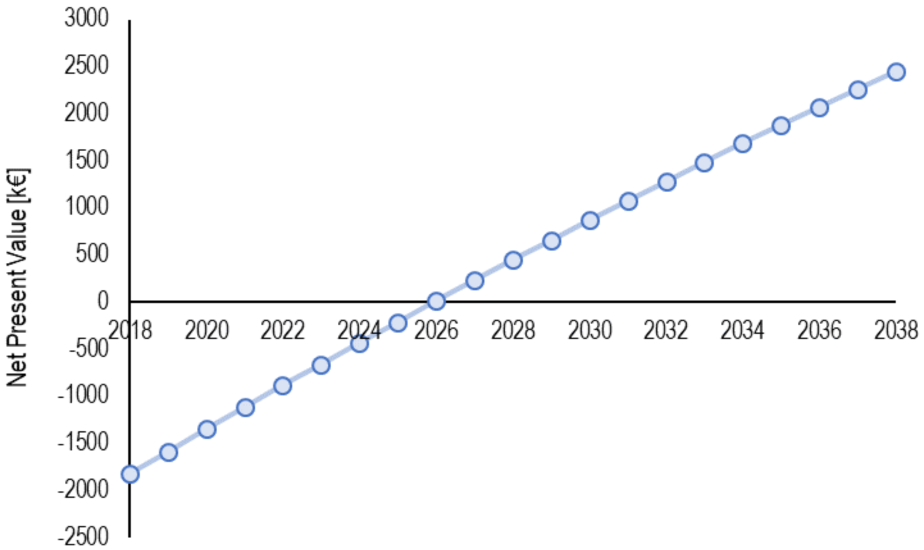


Figure 3. Variation of Net Present Value (k€) during WWTP lifetime.

The NPV values are plotted as a function to time (years) (Figure 3), indicating that positive values can be reached after 8 years of the operation of the nutrients recovery system.

Few data are available in the literature in terms of payback periods (PP) for the implementation of nutrients recovery option on WWTPs. The most successful technology in terms of wide deployment is the P recovery units from side-streams of sludge anaerobic digestion. Published reports from technology suppliers or WWTP facilities show that similar PPs have been reported from 10 to 20 years, as it depends mainly on the price allocated for recovered struvite, which fluctuates from negative values to positive values (300 €/ton struvite) (Cornel and Schaum, 2009; Dockhorn, 2009; Peng et al., 2018).

The financial rations were calculated in order to assess the feasibility of implementing a zeolite filtration system for nutrients recovery from the BLI-WWTP and are summarized in Table 4.

Table 4: Financial indexes estimated according for the nutrients recovery in the BLI-WWTP

Net Present Value [k€]	2354.2
Internal Rate of Return [%]	14.9
Return of Investment [%]	356.95
Payback Period [years]	7.4

As shown in results (Table 4), the investment in nutrients recovery system is economically feasible with a short PP and the IRR is greater than the discount rate considered. It is worth mentioning that these results are due to the existence of the UF unit as part of the regeneration station. Otherwise, the cost of the UF equipment and the installation of its control systems is estimated at 9.1M € (Depuradora Baix Llobregat S.A., 2007) and the results of the financial ratios would be less favorable as summarized in Table 5.

Table 5: Financial ratios estimated according for the nutrients recovery in the BLI-WWTP including UF unit

Net Present Value [k€]	-6396
Internal Rate of Return	-4.20
Return of Investment [%]	60
Payback Period [years]	44.4

Thus, the implementation of this technology for phosphorus and nitrogen recovery from wastewater secondary treated effluent is not feasible for small WWTPs that do not have tertiary treatment facilities based on membrane technologies (e.g., UF).

3.2. Sensitivity analysis

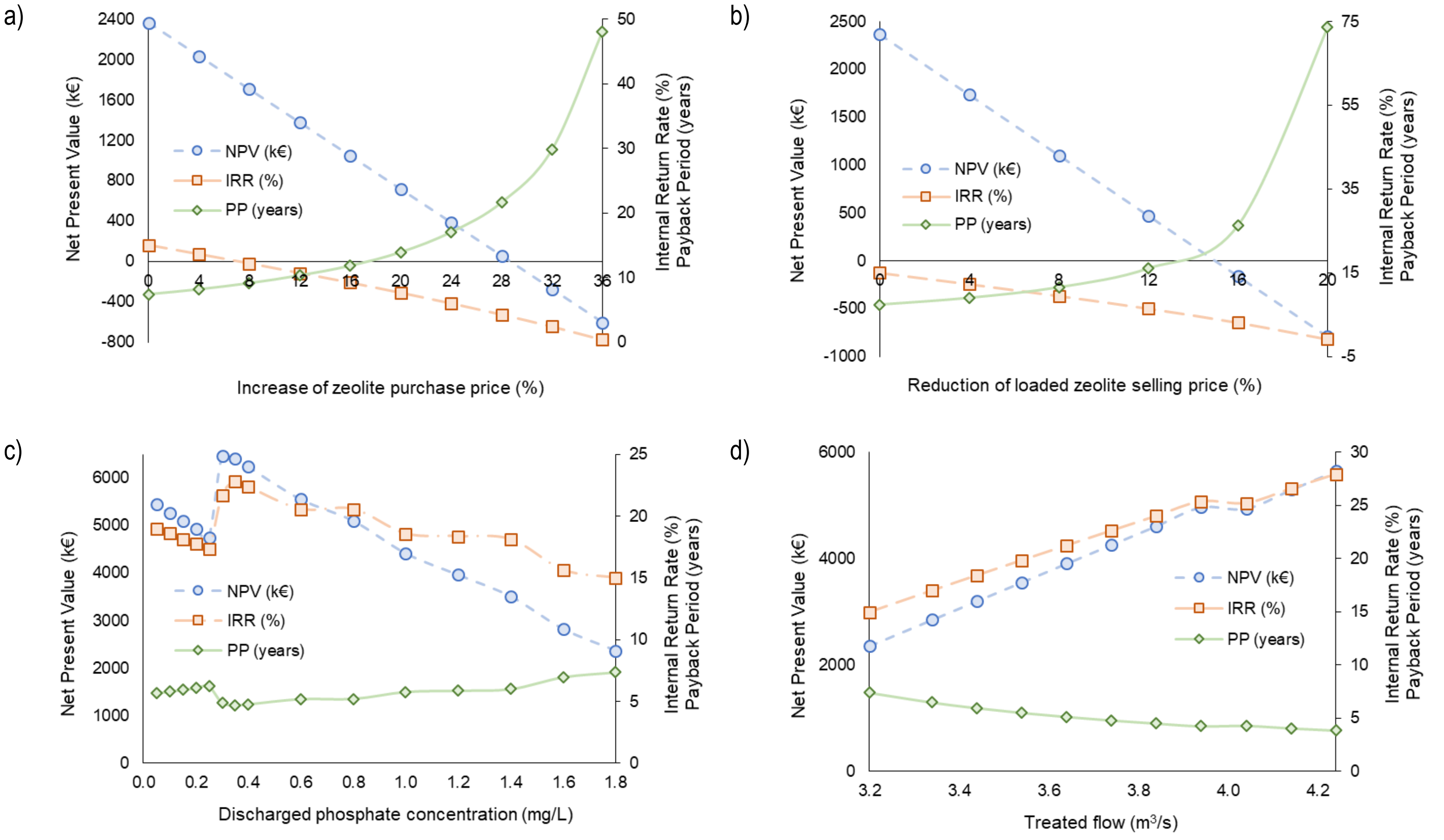
Considering that a lifetime of 20 years has been defined for this analysis, it is expected that some parameters will not be constant. Then, a sensitivity analysis was performed considering five scenarios as follows: i) increasing the cost of zeolite; ii) reduction of the market price of loaded zeolite rich in nutrients; iii) reducing phosphorus discharge limit; iv) increasing treated flow-rate, and v) variation of the discount rate. The sensitivity analysis was carried out considering the variations in the following key parameters:

i. The price of raw and loaded zeolites is assessed with variations of 4% taking into account possible market fluctuations as well as Retail Price Index increase along the project lifetime.

ii. The variation of phosphorus discharge limit is set at 0.2 mg/L for concentrations higher than 0.4 mgP/L and at 0.05 mg/L for concentrations lower than 0.4 mgP/L. These two variation of the discharge limits are set according to technical possibilities for reducing phosphorus content in wastewater treated effluents.

iii. The WWTP treated flow is assessed in increment intervals of 0.1 m^3/s according to the increase of the population in the Metropolitan Area of Barcelona and the trend in water consumption shown in the last five years.

iv. The variation of the discount rate evaluates the case of investment for private companies with not predictable growth (20%), private companies that are scaling predictably (10%) as well as public companies (2.5%). In addition, other intermediate values of the discount rate were studied. The financial ratios resulting from the sensitivity analysis are shown in the Figure 4.


a)
Net Present Value (k€)
2400
2000
1600
1200
800
400
0
-400
-800
NPV (k€)
IRR (%)
PP (years)
0
4
8
12
16
20
24
28
32
36
50
40
30
20
10
0
Internal Return Rate (%)
Payback Period (years)
Increase of zeolite purchase price (%)
b)
Net Present Value (k€)
2500
2000
1500
1000
500
0
-500
-1000
NPV (k€)
IRR (%)
PP (years)
0
4
8
12
16
20
75
55
35
15
-5
Internal Return Rate (%)
Payback Period (years)
Reduction of loaded zeolite selling price (%)
c)
Net Present Value (k€)
6000
5000
4000
3000
2000
1000
0
NPV (k€)
IRR (%)
PP (years)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
25
20
15
10
5
0
Internal Return Rate (%)
Payback Period (years)
Discharged phosphate concentration (mg/L)
d)
Net Present Value (k€)
6000
4000
2000
0
NPV (k€)
IRR (%)
PP (years)
3.2
3.4
3.6
3.8
4.0
4.2
30
25
20
15
10
5
0
Internal Return Rate (%)
Payback Period (years)
Treated flow (m³/s)

e)

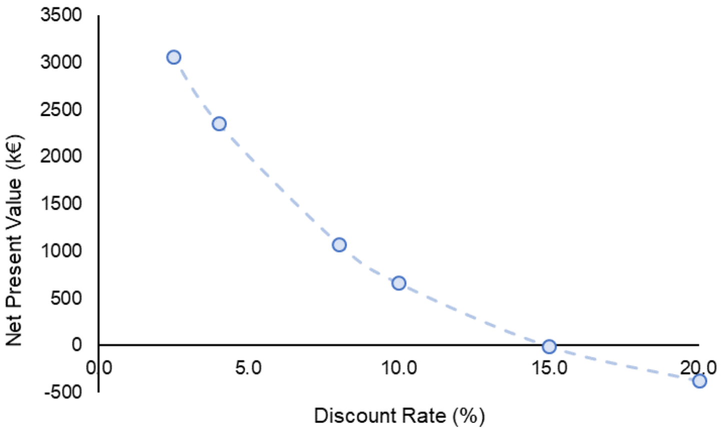


Figure 4: Variation of financial ratios by varying a) the zeolite purchase price; b) the zeolite loaded selling price; c) the phosphorus discharge limit; d) the treated flow; and e) the discount rate.

Increasing the cost of zeolite: As is shown in Figure 4a), with an increase in the purchase price of zeolite higher than 28%, an IRR of 3.9 is obtained, lower than the considered discount rate (4%); as well as a negative NPV. These results indicate that the implementation of nutrients recovery system for nutrient recovery is not economically feasible.

As the Ze-Ca is obtained by hydrothermal synthesis from fly ash (Querol et al., 1996), it is important to improve the efficiency of the process to avoid a significant increase in the cost of the sorbent as well as reduce environmental impact of chemical and energy consumption in the synthesis stage. The main reduction of the zeolite cost, according to the analysis of the synthetic route of the zeolite production, is associated to the final stage of drying. As the sorption process could be carried out using zeolites in a slurry mode the cost of the zeolite could be reduced by a factor of two if the zeolites are not dried (Industrias Químicas del Ebro, n.d.).

Reduction of the market price of loaded zeolite with nutrients: Sensitivity analysis reported that if zeolite selling price decreases over 15 %, the IRR would be lower than the discount rate of 4% and the PP would be 23 years, which means that the investment related to the construction of zeolite filtration tanks and pumping system would not be recovered along the project lifetime.

Since there is a great interest in the recovery of nutrients from WWTP, it is feasible to expect a reduction in the price of phosphorus-based fertilizer. Therefore, the efficiency of the sorption process is a key parameter that would allow increasing the N and P content in the loaded sorbent and increase its value in the market.

In the case of Europe, the inclusion of phosphate rock as one of the elements inside the Critical Raw Materials List (European Commission, 2017), the recovery of P from secondary resources will be mandatory. It has been estimated that up-to 30-40% of the total P needs at EU level could be recovered from the urban waste water cycle, and this has been traduced that in countries like Switzerland recovery of nutrients from WWTP is an obligation from 2016 (United Nations World

Water Assessment Programme, 2017). The main initiatives have been centered on the recovery of P from sewage sludge side-streams as struvite or as phosphoric from mono-incineration ashes of sewage sludge. In both cases the economic feasibility of the technologies is not clear; however, a policy and regulatory framework is being developed to support both recovery options.

Reducing phosphorus discharge limit: As the proposed WWTP configuration implies the installation of zeolite filtration tanks in only 7 working lines in order to minimize the CAPEX, the reduction of discharge limits implies the need of more filtration tanks. Thus, more investment is needed for the installation of additional filtration tanks and related pumping systems as well as a for UF membranes due to the shorter lifetime, which results in a fluctuation of the financial ratios shown in Figure 4c.

However, more restrictive regulation in phosphate discharge limits would not affect negatively the economic feasibility of the implementation of the nutrients recovery system. On the contrary, as shown in Figure 4c, a stricter regulation would lead to an increase in NPV and IRR, as well as a reduction in the PP.

Increasing treated flow: Increasing treated flow leads to a slightly improvement of all financial ratios according to sensitivity analysis, which corresponds to the expected increase in treated capacity of WWTP and consequently more loaded zeolites could be produced and potentially disposed as fertilizer.

Variation of the discount rate: as can be seen in Figure 4e), the fluctuation of the discount rate could lead to a significant variation of NPV during project lifetime, since the sensitivity analysis reported negative NPV values when considering a discount greater than 15% while if considering the water management is carried out by a public company, it is obtained 3063 k€ as NPV.

After conducting the financial assessment of the implementation of zeolite filtration system for nutrient recovery, an average OPEX/treated flow of 0.119 €/m^3 was obtained, significantly lower than 0.15 €/m^3 for PhosphoReduc (see Supplementary Material). If it is compared with Necovery treatment, which is currently being developed by CETaqua for Nutrient and Energy Recovery in Waste Water Treatment Plants by pre-concentration and Adsorption processes, the operating cost is slightly higher than 0.114 €/m^3, reported in a medium size WWTP in Barcelona metropolitan Area.

Currently, the operating cost of BLI-WWTP is estimated at 0.084 €/m^3, slightly lower than 0.119 €/m^3 after implementing the zeolite filtration system. However, if an analysis is made of total value of the recovery of nutrients taking into account the savings in chemicals, the production of fertilizers, the improvement of the operation and the performance in the BLI-WWTP, the net balance is an economic benefit of 0.002 €/m^3.

Furthermore, it is important to point out other non-economic benefits (externalities) as protection and improvement of Water Quality or food Security improvement and social equity (Mayer et al., 2016). Thus, the implementation of zeolite filtration system for nutrient recovery from WWTP secondary effluents leads to additional benefits as:

i. Promotes circular economy by valorizing the fly ash, a byproduct of coal power plant, as a sorbent for nutrients recovery (Mayer et al., 2016)
ii. Reduces the environmental issues due to the metal lixiviation of fly ash disposal (Izquierdo and Querol, 2012)

However, internalizing these benefits is beyond the scope of this study, although it can certainly provide a better economic equilibrium when positive externalities are expressed in monetary terms.

4. Conclusions

In this study, the feasibility of implementing a simultaneous ammonium and phosphate recovery system, based on the sorption by a calcium-activated synthetic zeolite, in a large WWTP (>1.000.000 PE) as it is the case of the BLI-WWTP in the Barcelona Metropolitan Area was assessed.

Results show that the implementation of this alternative technology in BLI-WWTP is economically profitable, since it reported a PP of 7.5 years and an IRR of 15%, higher than considered discount rate. It is important to point out that these values are obtained due to the existence of an UF unit in the regeneration station of the studied WWTP. Otherwise, the required CAPEX would be considerable higher and the economic evaluation may not result feasible.

Sensitivity analysis showed that the critical parameters in economic feasibility are those related with the purchase or sale of the sorbent, an increase in the cost of the sorbent (28%) and a decrease in the sale price (15%) could make the implementation economically unfeasible.

More research is needed in synthesis and activation of zeolites to reduce the effects of price fluctuation of the sorbent. In addition, further studies on the performance of nutrients uptake and the potential use of loaded zeolites at the pilot plant scale are needed, which will allow to evaluate the economic feasibility of its implementation.

Finally, before the implementation of the nutrients recovery system in a WWTP it is necessary to consider the logistics necessary to evacuate 5000 tons/y of loaded zeolites, which according to Blachowski (2014), would be evacuated weekly through road transport by using trucks.

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References

Abeynaike, A., Wang, L., Jones, M.I., Patterson, D.A., 2011. Pyrolysed powdered mussel shells for eutrophication control : effect of particle size and powder concentration on the mechanism and extent of phosphate removal. Asia-Pacific J. Chem. Eng. 6, 231–243. https://doi.org/10.1002/apj

Alkas, D., Beler Baykal, B., Kinaci, C., 2013. Implementation of natural zeolite for filtration of secondary municipal effluents. Desalin. water Treat. 51, 3047–3051.

Amann, A., Zoboli, O., Krampe, J., Rechberger, H., Zessner, M., Egle, L., 2018. Environmental impacts of phosphorus recovery from municipal wastewater. Resour. Conserv. Recycl. 130, 127–139.

Àrea Metropolitana de Barcelona, 2017a. EDAR del Prat de Llobregat [WWW Document]. Instal. y Equipamientos. URL https://goo.gl/c9WWS4

Àrea Metropolitana de Barcelona, 2017b. EDAR del Prat de Llobregat [WWW Document]. Instal. y Equipamientos.

Barca, C., Gérente, C., Meyer, D., Chazarenc, F., Andrès, Y., 2012. Phosphate removal from synthetic and real wastewater using steel slags produced in Europe. Water Res. 46, 2376–

84. https://doi.org/10.1016/j.watres.2012.02.012

Bashar, R., Gunkor, K., Karthikeyan, K.G., Barak, P., 2018. Cost effectiveness of phosphorus removal processes in municipal wastewater treatment. Chemosphere 197, 280–290.

Bennett, E.M., Schipanski, M.E., 2013. Chapter 8: The Phosphorus Cycle, in: Fundamental of Ecosystem Science. Elsevier.

Blachowski, J., 2014. Spatial analysis of the mining and transport of rock minerals (aggregates) in the context of regional development. Environ. Earth Sci. 71, 1327–1338.

Blasco Saiz, P., 2010. Depósito de agua potable de 1000 m3 de capacidad en Agudo (Ciudad Real).

Cornel, P., Schaum, C., 2009. Phosphorus recovery from wastewater: needs, technologies and costs. Water Sci. Technol. 59, 1069–1076.

Depuradora Baix Llobregat S.A., 2007. Aprovechamiento del agua regenerada de la EDAR del Baixo Llobregat para Riego Agrícola.

Dockhorn, T., 2009. About the economy of phosphorus recovery, in: International Conference on Nutrient Recovery from Wastewater Streams. Vancouver.

Driscoll, C.T., Whitall, D., Aber, J., Boyer, E., Castro, M., Cronan, C., Goodale, C.L., Groffman, P., Hopkinson, C., Lambert, K., Lawrence, G., Ollinger, S., 2003. Nitrogen pollution in the northeastern United States: Sources, effects and management options. Bioscience 53, 357–374.

Egle, L., Rechberger, H., Zessner, M., 2015. Overview and description of technologies for recovering phosphorus from municipal wastewater. Resour. Conserv. Recycl. 105, 325–346.

European Commission, 2017. 2017 list of Critical Raw Materials for the EU. Brussels.

Federal Reserve Bank of St. Louis, 2018. Interest Rates, Discount Rate for Euro Area [WWW Document]. Interes. Rates, Discount Rate Euro Area. URL https://fred.stlouisfed.org/series/INTDSREZQ193N (accessed 10.21.18).

Foreman, G.P., 1985. Slow Rate Sand Filtration With and Without Clipnoptilolite: A Comparison of Water Quality and Filtration Economics. Utah University.

Galloway, J., Cowling, E., 2002. Reactive nitrogen and the world: Two hundred yeards of change. Ambio 31, 64–71.

Groffman, P.M., Rosi-Marshall, E.J., 2013. The Nitrogen Cycle, in: Weathers, K.C., Strayer, D.L., Likens, G.E. (Eds.), Fundamentals of Ecosystem Science. Elsevier, London, pp. 212–245.

Haddad, K., Jellali, S., Jaouadi, S., Beltilfa, M., Mlayah, A., Hamzoui, A.H., 2015. Raw and treated marble wastes reuse as a low cost material for phosphorus removal from aqueous solutions: efficiencies and mechanisms. Comptes rendus Chim. 18, 75–87.

Hansen, 1997. Comparison of Sand and Zeolite Filter Media: Head Loss for Gravity Beds. New mexico State University.

He, X., Xu, W., Sun, W., Ni, J., 2012. Phosphate removal using compounds prepared from paper sludge and fly ash. Environ. Earth Sci. 70, 615–623. https://doi.org/10.1007/s12665-012-2145-6

Hermassi, M., Valderrama, C., Gibert, O., Moreno, N., Font, O., Querol, X.Batis, N.H., Cortina, J.L., 2016. Integration of Powdered Ca-Activated Zeolites in a Hybrid Sorption–Membrane Ultrafiltration Process for Phosphate Recovery. Ind. Eng. Chem. Res. 55, 6204–6212.

Industrias Químicas del Ebro, n.d. Grupo IQE [WWW Document]. URL www.ieq.es (accessed 10.21.18).

Instituto Nacional de Estadística, 2017. Variaciones del Índice de Precios de Consumo.

Izquierdo, M., Querol, X., 2012. Leaching behaviour of elements from coal combustion fly ash: An overview. Int. J. Coal Geol. 94, 54–66.

Jaouadi, S., Wahab, M.A., Anane, M., Bousselmi, L., Jellali, S., 2014. Powdered marble wastes reuse as a low-cost material for phosphorus removal from aqueous solutions under dynamic conditions. Desalin. water Treat. 52, 7–9.

Kabbe, C., Kraus, F., Remy, C., 2017. Circular Economy - Challenges and Opportunities for Phosphorus Recovery & Recycling from Wastes in Europe, in: SYMPHOS 2017 - 4th International Symposium on Innovation and Technology in the Phosphate Industry.

Köck-Schulmeyer, M., Ginebreda, A., Postigo, C., López-Serna, R., Pérez, S., Brix, R., Llorca, M., López de Alda, M., Petrovic, M., Munné, A., Tirapu, L., Barceló, D., 2011. Wastewater reuse in Mediterranean semi-arid areas: The impact of discharges of tertiary treated sewage on the load of polar micro pollutants in the Llobregat river (NE Spain). Chemosphere 82, 670–678. https://doi.org/10.1016/j.chemosphere.2010.11.005

Maaβ, O., Grundmann, P., von Bock und Polach, C., 2014. Added-value from innovative value chains by establishing nutrient cycles via struvite. R$esources, Conserv. Recycl. 87, 126–136. https://doi.org/http://dx.doi.org/10.1016/j.resconrec.2014.03.012

Machado, A.P., Urbano, L., Brito, A.G., Janknecht, P., Salas, J.J., Nogueira, R., 2007. Life cycle assessment of wastewater treatment options for small and decentralized communities. Water Sci. Technol. 56, 15–22.

Mas-Pla, J., Castañón, O., Munné, A., Prat, N., Saurí, D., Alcántara, V., Roca, J., Costejà, M., Font, N., 2006. La Directiva marc de l'Aigua a Catalunya. Barcelona.

Mayer, B.K., Baker, L.A., Boyer, T.H., Drechsel, P., Gifford, M., Hanjra, M.A., Parameswaran, P., Stoltzfus, J., Westerhoff, P., Rittmann, B.E., 2016. Total Value of Phosphorus Recovery.

Environ. Sci. Technol. 50, 6606–6620. https://doi.org/10.1021/acs.est.6b01239

Oenema, O., Bleeker, A., Braathen, N.A., Budnakova, M., Bull, K., Cermak, P., Geupel, M., Hicks, K., Hoft, R., Kozlova, N., Leip, A., Spranger, T., Valli, L., Velthof, G., Winiwarter, W., 2011. Nitrogen in current European policies.

Originblue, 2017. Hollow Fiber Membrane Element. Zhejiang.

Peng, L., Dai, H., Wu, Y., Peng, Y., Lu, X., 2018. A comprehensive review of phosphorus recovery from wastewater bt crystallization processes. Chemosphere 197, 768–781.

Querol, X., Moreno, N., Alastuey, a, Juan, R., Ayora, C., Medinaceli, a, Valero, a, Productos, C., 1996. Synthesis of high ion exchange zeolites from coal fly ash. Geol. Acta 1, 49–57.

Reijnders, L., 2014. Phosphorus resources, their depletion and conservation, a review. Resour. Conserv. Recycl. 93, 32–49.

Ribanova, I., Dimitrova, S., Lambeva, R., Wintgens, T., Stemann, J., Remmen, K., 2017. Phosphorus recovery potential in Sofia WWTP in view of the national sludge management strategy. Resour. Conserv. Recycl. 116, 152–159.

Roberts, T.L., Johnston, A.E., 2015. Phosphorus use efficiency and management in agriculture. Resour. Conserv. Recycl. 105, 275–281.

Röhling, S., 2010. Globale Verfügbarkeit von Dünger- und Energierohstoffen, in: AHT Niederorschel Und Der Volksbank Dransfeld Proceedings.

Scholz, M., 2017. Creating a circular economy for phosphorus fertilizers. Fertil. Focus 36–41.

Scholz, R.W., Ulrich, A.E., Eilittä, M., Roy, A., 2013. Sustainable use of phosphorus: a finite resource. Sci. Total Environ. 461–462, 799–803. https://doi.org/10.1016/j.scitotenv.2013.05.043

United Nations World Water Assessment Programme, 2017. Wastewater: the Untapped Resource. Paris.

United States Department of Defense, 2011. Technology Readiness Assessment (TRA) Guidance.

van der Hoek, J.P., de Fooij, H., Struker, A., 2016. Wastewater as a resource: Strategies to recover resources from Amsterdam's wastewater. Resour. Conserv. Recycl. 113, 53–64.

Xiong, J., Qin, Y., Islam, E., Yue, M., Wang, W., 2011. Phosphate removal from solution using powdered freshwater mussel shells. Desalination 276, 317–321. https://doi.org/10.1016/j.desal.2011.03.066

You, X., Farran, A., Guaya, D., Valderrama, C., Soldatov, V., Cortina, J.L., 2016a. Phosphate removal from aqueous solutions using a hybrid fibrous exchanger containing hydrated ferric oxide nanoparticles. J. Environ. Chem. Eng. 4, 388–397. https://doi.org/http://dx.doi.org/10.1016/j.jece.2015.11.032

You, X., Guaya, D., Farran, A., Valderrama, C., Cortina, J.L., 2016b. Phosphate removal from aqueous solution using a hybrid impregnated polymeric sorbent containing hydrated ferric oxide (HFO). J. Chem. Technol. Biotechnol. 91, 693–704. https://doi.org/10.1002/jctb.4629

You, X., Valderrama, C., Cortina, J.L., 2017a. Simultaneous recovery of ammonium and phosphate from simulated treated wastewater effluents by activated calcium and magnesium zeolites. J. Chem. Technol. Biotechnol. 92, 2400–2409. https://doi.org/10.1002/jctb.5249

You, X., Valderrama, C., Querol, X., Cortina, J.L., 2017b. Recovery of Ammonium by Powder Synthetic Zeolites from Wastewater Effluents: Optimization of the Regeneration Step. Water, Air, Soil Pollut. 228. https://doi.org/doi.org/10.1007/s11270-017-3577-0