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Phosphorus in Balance: Evaluating the Costs and Benefits of a Circular Economy Approach

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Abstract

This paper presents a comprehensive cost-benefit analysis of producing alternative phosphorus (P) fertilizers from recycled water treatment residuals (Fe-WTR) and cowshed effluents. The cost-benefit values of Fe-WTR are compared to the net costs of recycling P using a synthetic adsorbent (commonly used practice-layered double hydroxide, P-LDH) and the costs of commercial fertilizers. Dairy wastewater is used as a source of P. The cost of 1 ton P using the Fe-WTR process is €329. In contrast, synthetic adsorbents (P-LDH) incur significantly higher costs, amounting to €3329 per ton, underscoring the economic advantage of utilizing waste-derived materials. Adopting Fe-WTR fertilizer not only offers substantial cost savings by avoiding landfill fees (€40 per ton) and wastewater discharge fines (€500 per ton) but also reduces environmental impacts when compared to the use of commercial P fertilizers (non-recycled P). The Fe-WTR method mitigates eutrophication and pollution, presenting the dual benefit of cost-effectiveness and environmental protection, which exceeds the common P recycling practice (LDH). Our conclusions are based on production processes in Israel and compared to previous cost estimations at the world level, assessing the potential gain from such circular production of P globally. Recycling P from waste streams can be economically viable and environmentally preferable at small and large economic scales, supporting global sustainability goals.

Keywords: cost-benefit analysis, phosphorus recycling, fertilizers, water treatment (Fe-WTR), layered double hydroxide, circular economy

1. Introduction

Phosphorus (P) plays an indispensable role in global agriculture, underpinning the sector's ability to meet the world's increasing food demands (Sultenfuss and Doyle., 1999). As a vital component of plants, P is essential for energy transfer, photosynthesis, and cell division, making it a cornerstone of crop productivity and plant health. Agricultural intensification, aimed at achieving higher yields to feed a burgeoning population, has further entrenched the reliance on P-based fertilizers and increasing mining activities that disrupt the natural landscape and ecosystems in the vicinity of the quarry due to land-use violations, air emissions, water pollution, and noise (Cordell et al., 2009; Cordell and White, 2011). Reliance on P fertilizers has been pivotal in boosting food production (Cordell and White, 2013; FAO, 2022); therefore, recent years have seen increased research and investment in more efficient P-fertilizer production at lower environmental externalities and lower costs.

The global cost of processing and transporting P fertilizers is primarily determined by energy costs and environmental costs. Phosphorite rocks are one of the most widely traded commodities on the international market, with approximately 220 million tons transported annually (Cordell and White, 2011; USGS, 2023). Phosphorus fertilizer market prices are contingent on international demand and the geopolitical stability of a limited number of countries who possess major P resources: P stocks are primarily located in Morocco (69.44%), Egypt (3.89%), Tunisia (3.47%), Algeria (3.09%), China (2.64%), Brazil (2.2%), South Africa (2.2%), Saudi Arabia (1.94%), Australia (1.53%), and the United States (1.39%) (Table 1) (Cordell and White, 2011; USGS, 2023). However, global P production is currently led by China (41%), Morocco (16%), the United States (9%), and Russia (6%)

with a total of 220.75 million metric tons in 2023 (US National Minerals Information Center, 2023) (Figure. 1). (Note 1)

Table 1. Phosphorus World Mine Reserves

Country	Reserves (billion metric tons)	Reserves (%)
Morocco and Western Sahara	50,000,000	69.44
Egypt	2,800,000	3.89
Tunisia	2,500,000	3.47
Algeria	2,200,000	3.06
China	1,900,000	2.64
Brazil	1,600,000	2.22
South Africa	1,600,000	2.22
Saudi Arabia	1,400,000	1.94
Australia	1,100,000	1.53
United States	1,000,000	1.39
Jordan	1,000,000	1.39
Finland	1,000,000	1.39
Other countries	2,600,000	5.65

Database: US National Minerals Information Center, 2023; USGS, 2023.

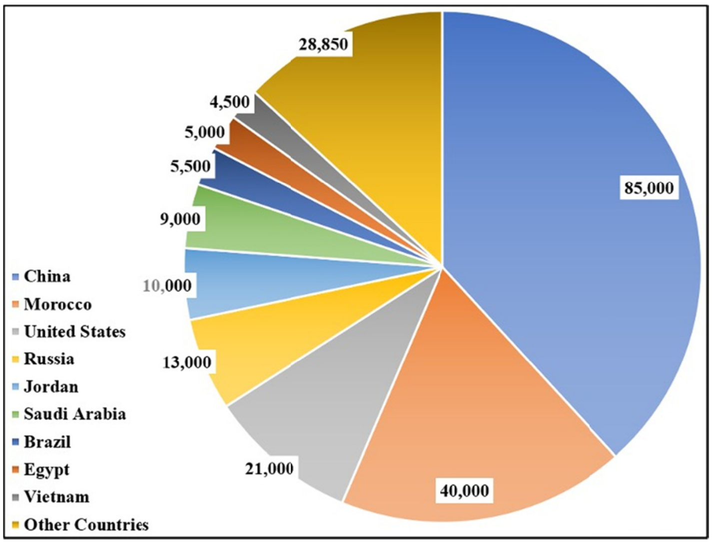

Figure 1. Phosphorus World Mine Production

Database Source: US National Minerals Information Center, (2023)

The market price of *P* fertilizer is forecast to increase as long as demand continues to rise and no new production substitutes are available (Cordell and White, 2011; The World Bank, 2017). Al Rawashdeh (2023) has estimated the short-and long-run price elasticities of demand for *P* at –0.003 and –0.061, respectively, meaning highly inellastic. This implies that a 1% increase in the demand for *P* will lead to a 3.33% price increase in the short run, and a 16.4% price increase in the long run. These results are consistent with previous results, including those of Denbaly and Vroomen (1993), who found that price elasticities for phosphate were historically inelastic.

Moreover, the extraction and refinement of phosphorite rock, a primary source of *P*-fertilizers for agriculture, is a process fraught with environmental and ecological implications. In producing one ton of P fertilizer, this process yields approximately five tons of phospho-gypsum, a by-product laden with carbon, radioactive elements, and heavy metals such as cadmium and uranium that are toxic to soils and humans (Carpenter and Bennett, 2011; Cordell et al., 2009; Cordell and White, 2011). Such by-products represent a significant environmental hazard, contributing to the growing concern over industrial carbon footprints and the contamination of natural ecosystems. Not only does overuse of *P* impact the environemnt, it also has direct economic costs, raising the costs of agricultural production. The fluctuation in the price of Phosphorus and continuous increase in its market price over time is presented in Figure 2. Moreover, the market price index of Phosphorus is strongly correlated with agricultural production prices, reinforcing the need to develop additional alternatives to Phosphorus reserves (Figure 2). Based on the database of the Federal Reserve Bank, we have estimated the long run correlation coefficient (R) between the Phosphorus fertilizers price-index and the farm products price-index for the years 1950–2020 to be R=0.81.

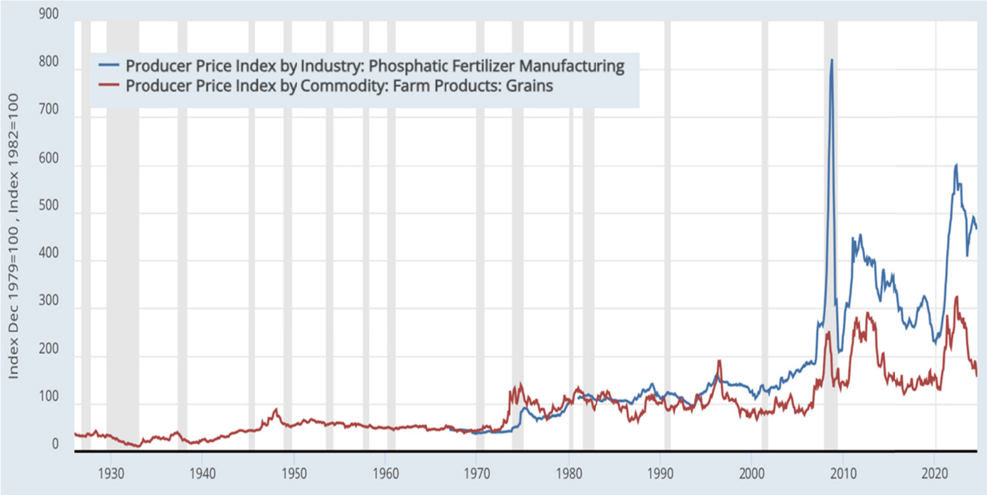

Figure 2. Producer Price Index by Industry, Phosphatic Fertilizers and Farm Production (Grain), 1930–2023. Shaded areas indicate U.S. recessions periods.

Data Source: U.S. Bureau of Labor Statistics, Producer Price Index by Industry. Retrieved from the Federal Reserve Bank, 2024. Correlation coefficient between phosphate price index and farm product index is R=0.81.

The primary objective of this paper is to conduct a comprehensive cost-benefit analysis of implementing a circular economy framework in the production of P. This analysis will take into account the economic and environmental ramifications of transitioning from using non-recycled P fertilizers and layered double hydroxide (LDH) recycled P, to adopting a circular approach that incorporates the recycling of P via the iron-water treatment residual (Fe-WTR) process. The Fe-WTR process embodies the efficient reuse of resources, thereby fostering their long-term sustainability, lessening the burden of environmental waste and related economic costs, and consequently contributing to global economic growth and ecological health (Berg et al., 2018; Kirchherr et al., 2017). Moreover, this shift decreases our dependence on resource-rich nations as discussed by Smol (2019), reinforces local agricultural production and overall landscape value (Van Kauwenbergh, 2010; Linderholm et al., 2012; DiSegni, 2013). Ultimately, this research will quantify the tangible benefits and highlight the potential challenges of implementing a circular economy in P production.

2. Circular P Production

To address the dual challenges of P management, namely, the reliance on non-renewable rock phosphate and the associated water pollution, there is a pressing need to embrace alternative approaches that encapsulate the principles of a circular economy. Recycling P from wastewater and reintegrating it into agricultural systems emerges as a sustainable solution with the potential to significantly reduce our dependence on mined rock phosphate (Barnea et al., 2012; Cordell et al., 2009; Steen, 1998; Wendling et al., 2013). This strategy involves reprocessing wastewater to recover P, thereby transforming a waste product into a valuable resource. Such an approach not only helps conserve finite P reserves but also mitigates the environmental impacts of P run-off. By reintroducing recycled P into the agricultural cycle, we can close the loop, minimizing the leaching and eutrophication that result from the excessive use of conventional P fertilizers. Moreover, recycling P aligns with the broader objectives of resource conservation, waste reduction, and economic efficiency, which are at the heart of a circular economy. This paradigm shift presents an opportunity to reassess and redesign the entire P life cycle, from extraction to use, recovery, and reuse, thereby creating a more resilient agricultural system that can withstand the challenges of resource scarcity and environmental degradation.

2.1 Phosphorus Recycling Technology: Fe-WTR

Water treatment residuals (WTR), a by-product of clarification pretreatment of surface water, e.g., in the seawater desalination industry, offer a significant yet underutilized potential for P recovery. These residuals result from the addition of coagulants such as ferric chloride ($FeCl_3$) or aluminum sulfate $Al_2(SO_4)_3$ to the treated water, which, under neutral pH conditions, precipitate into a heterogeneous sludge with high surface area and a pronounced affinity for the adsorption of anions, including phosphate ions (Ippolito et al., 2011; Zohar et al., 2020; Zohar and Forano, 2021). Conventionally, the desalination sector has leaned towards the environmentally unsustainable practice of landfilling massive quantities of iron-rich WTR (Fe-WTR). This process includes a pre-treatment step where the Fe-WTR is washed with tap water at the desalination plant to reduce the salinity accumulated from seawater, followed by air drying. If the salt remains in the Fe-WTR, it can leach into the soil when used as an alternative fertilizer, causing major problems such as soil salinization, which inhibits plant growth (Machado and Serralheiro, 2017; Okur and Örçen, 2020; Singh, 2015), constituting a missed opportunity for resource recovery and a source of environmental degradation (Netanyahu, 2017).

The Fe-WTR process offers two main benefits: it protects the environment by reducing waste that would otherwise go to landfills and generate environmental hazards, and increases P availability using a process of recycling wastewater through methods such as co-precipitation or adsorbents. Co-precipitation can be accomplished using chemicals such as $FeCl_3$ and $Al_2(SO_4)_3$, to produce minerals such as struvite ($NH_4MgPO_4 \cdot 6H_2O$), strengite ($FePO_4 \cdot 2H_2O$), hydroxyapatite ($Ca_5(PO_4)_3(OH)$), fluorapatite ($Ca_5(PO_4)_3F$), and chlorapatite ($Ca_5(PO_4)_3Cl$) (Fink et al., 2016; Hughes and Rakovan, 2019; Roldán et al., 2002; Wilfert et al., 2015). Adsorption can be achieved using adsorbing materials such as LDHs, oxides and oxyhydroxides, porous nanosilicates, and polymer ligand exchangers (Bacelo et al., 2020; Wendling et al., 2013; Zohar et al., 2017; Zohar and Forano, 2021). The adsorbent materials efficiently capture P and demonstrate very limited release capability, posing a challenge to reusability (Cordell et al., 2011; Wendling et al., 2013). Moreover, this approach does not align with circular economy principles of reducing waste materials and may not be cost-effective (Loganathan et al., 2014). However, using wastewater as a P source (referred to as Fe-WTR) not only adheres to sustainability but also improves P lability and phyto-availability since organic compounds in wastewater weaken P binding to the adsorbent surfaces (Banet et al., 2020; Song et al., 2011; Yang. et al., 2006). This recent innovative approach of using dairy wastewater, with Al- and Fe-based WTRs, has been developed and analyzed by Litaor et al., (2019); Zohar et al., (2020), Zohar et al., (2018), Zohar et al., (2017)); and Zohar and Forano, (2021).

Soil P-fixation processes immobilize P, severely restricting its availability to plants and thereby undermining the efficacy of fertilization efforts. To compensate for the resultant P deficiency, agricultural practices often resort to the overuse of fertilizers. This overuse initiates a cascade of environmental degradation, including leaching of excess nutrients into groundwater systems, pollution of water bodies, eutrophication of aquatic ecosystems, and creation of anoxic dead zones. Such zones inflict harm not only on water reservoirs but also on human economic activities such as fishing and tourism (Ayele and Atlabachew, 2021; De-Bashan and Bashan, 2004; Haygarth et al., 2013; Litaor et al., 2016, 2013). The nutrient-rich effluents emanating from municipal and agricultural sources, characterized by high P concentrations, exacerbate the problem, significantly contributing to the P load in waterways and furthering the eutrophication process. Thus there is a critical need for a paradigm shift in P management that aligns with the principles of a circular economy and mitigates the adverse environmental impacts associated with current practices.

2.2 Phosphorus Recovery Process

The subsequent section details the P recovery process by means of Fe-WTR, which forms the basis of this comprehensive cost-benefit evaluation. We note that the P cycle process in Fe-WTR is influenced by various chemical and physical conditions, including pH, temperature, particle size, solid-liquid ratio, ionic strength, and biological factors. These conditions can directly impact the amount of P adsorbed or removed from the solution, thereby affecting the overall efficiency of the process (Ganem et al., 2023; Muisa et al., 2020).

Zohar and Forano (2021) investigated the efficacy of two types of adsorbents for P recovery from wastewater. The first, a synthetic adsorbent, was a commercial calcined oxide material known as layered double hydroxide (LDH), with the formula $Mg_{0.7}Al_{0.3}O_{1.15}$, provided by KISUMA-Chemicals. The layered oxide structure of LDH contributes to high sorption capacity. The second was a recycled material derived from the residues of water treatment processes in desalination facilities, known as Fe-WTR, which comprises a heterogeneous mix of calcite, Fe hydroxides, clays, and organic matter from seawater. Both adsorbents were subjected to P loading using dairy wastewater after clarification with nanocomposites (Rytwo, 2012), resulting in adsorbents enriched with P and organic compounds, designated P-LDH and P-Fe-WTR (Fig. 4). Total P concentration was 7752 mg kg^{-1} in P-LDH and 6100 mg kg^{-1} in P-Fe-WTR.

According to Zohar and Forano (2021), who conducted a study using the same adsorbents, the concentrations of TDP (total dissolved P) released from the adsorbents indicate that P was significantly more labile in P-Fe-WTR than in P-LDH in 0.01M KCl solution. Upon mixing with dairy wastewater, P-Fe-WTR demonstrated superiority, yielding approximately 90 mg TDP kg^{-1}, compared to the 1.3–6.4 mg TDP kg^{-1} produced from P-LDH. Thus, despite P-Fe-WTR having a lower P content than P-LDH, it retained much higher P solubility.

Zohar et al. (2024) evaluated the potential for P-LDH and P-Fe-WTR to perform as P sources, i.e., facilitate P release and its subsequent assimilation in plant biomass. The efficiency of the recycled P was tested using lettuce (*Lactuca sativa*) as a bioindicator in pot experiments, being a plant requiring high P, with a short life cycle, high immunity to crop diseases, and rapid responses to drip irrigation and fertilization (Hoque et al., 2010). In their study, the P-Fe-WTR and P-LDH were applied at three doses (3, 7, and 11 g pot^{-1}), and were compared to a commercial slow-release fertilizer (positive control (superphosphate)) and untreated soil (negative control). The difference in performance was taken into consideration in our cost-benefit analysis. In this study, we will focus on the following treatments: commercial fertilizer, without P, P-Fe-WTR 11, and P-LDH 11.

Applying P-Fe-WTR 11 was comparable to the positive control, and was more effective than P-LDH-11 in releasing this essential nutrient in P-deficient soil. After the lettuce growth experiment, the lettuce leaves in the P-Fe-WTR 11 treatment measured 21.6±2.3 cm in length , similar to the positive control (approximately 22.1±1.2 cm) and significantly longer than the P-LDH 11 treatment (14.6±4.4 cm) ($F=11.8$, $p<0.05$) and the negative control (12.1±1.6 cm) ($F=70$, $p<0.05$) (Table 2 and Fig. 3). The dry biomass corresponded to leaf length (i.e., plant height), with the P-Fe-WTR 11 treatment producing 4.4±0.8 g, similar to the positive control (3.8±0.5 g) and significantly higher than the P-LDH 11 treatment (1.12±0.3 g) ($F=89.5$, $p<0.05$) and the negative control (0.85±0.1 g) ($F=115$, $p<0.05$) (Table 2 and Fig. 3). These results demonstrate that P-Fe-WTR promotes crop growth with an efficiency comparable to that achieved with commercial fertilizers. The organic compounds abundant in dairy effluents impacted organic and inorganic P binding in P-Fe-WTR 11, rendering a weaker binding than in P-LDH 11; due to its high sorption capacity and strength, LDH was less affected by the presence of the organic compounds, resulting in reduced P availability to the plant. Adding P-Fe-WTR 11 to soils provides a more readily available P source for plants than P-LDH 11, which is evident in biomass and leaf length.

These results demonstrate the similarity between lettuce grown using commercial fertilizer and lettuce treated with P-Fe-WTR 11. This indicates that the alternative P fertilizer can be effectively used in agriculture, providing P release efficiency comparable to that of commercial fertilizer. Furthermore, despite P-Fe-WTR 11 having a lower P content than P-LDH 11, it retained much higher P solubility and phyto-availability. The practical implication of these findings is that while synthetic materials prove more effective in removing excess P (e.g., treating polluted streams), recycled materials may serve as a valuable resource in P recycling, particularly when combined with additional recycling efforts, offering an alternative P fertilizer.

Table 2. Lettuce height (longest leaf length) and dry biomass on the last day of the growth period

Treatment	P source dose (g pot^{-1})	Dry Biomass (g pot^{-1}) (mean±s.d.)	Longest leaf length (cm) (mean±s.d.)
P-Fe-WTR 11	11	4.4±0.8	21.6±2.3
P-LDH 11	11	1.12±0.3	14.6±4.4
Commercial fertilizer	0.7	3.8±0.5	22.1±1.2
Unfertilized soil	0	0.85±0.1	12.1±1.6

Commercial fertilizer P-Fe-WTR 11 P-LDH 11 Unfertilized soil

Figure 3. Comparison of productivity using three P-fertilizers productivity, and unfertilized soil (Zohar et al., 2024). Experiments supports the superiority of the circular economy processes (Recycled P-Fe-WTR) compared to the alternatives, according to the specification in Table 2.

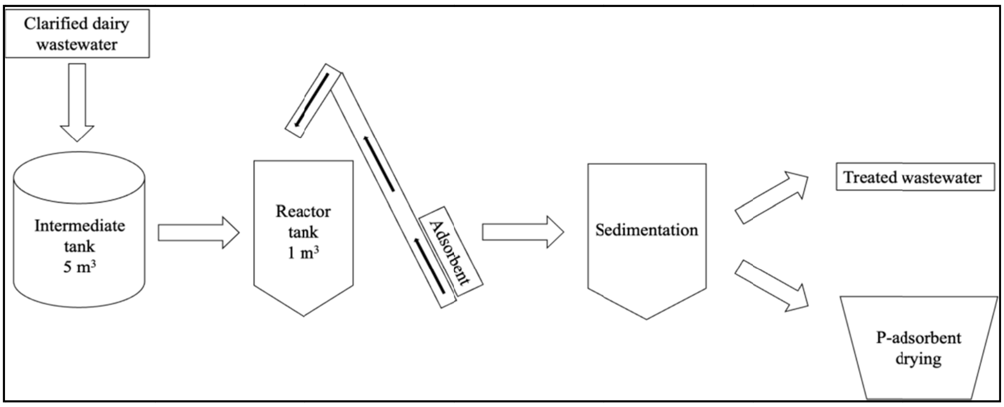

Figure 4. The circular technological of recovering P from dairy wastewater using adsorbents materials. Process detailed in Zohar and Forano, (2021)

3. Methodology: Cost Analysis of Alternative P Fertilizer Production

In the context of this study, a cost-benefit analysis was conducted to evaluate the economic viability and environmental impact of the circular reproduction of P as detailed above. This analysis takes into account the initial investment in the recovery process, operational costs, and the market value of the P-loaded adsorbents as alternative fertilizers. It also considers the environmental benefits derived from diverting waste from landfills, reducing the need for traditional mining, and mitigating water pollution through P removal. The analysis is critical for assessing the overall sustainability of the proposed circular economy approach, highlighting the trade-offs and synergies between economic efficiency and environmental stewardship.

3.1 Costs Analysis Approach

The production costs associated with creating alternative P fertilizers, such as P-Fe-WTR and P-LDH, are critical for determining the economic feasibility of the circular P production approach. Considering the most efficient and cost-effective practices known today, the associated production costs of both adsorbents depend on the dairy wastewater used as a P source, including the volume processed and the chemicals used. (Note 2) The clarification pretreatment of the dairy wastewater (solid-liquid separation), used in the presented case, comprised 3% nanocomposite (N/C 24) and 40% ZETAG 9088 (Rytwo, 2012), adding a cost of €204 per 111 L treated wastewater. While these chemicals are effective, as they efficiently remove organic solids but leave the high P content in solution, exploring other cost-effective alternatives for clarification methods is advisable. The cost analysis considers the energy required for production, measured in kilowatt-hours (kWh), and the total volume of wastewater treated, reported in cubic meters (m^3).

3.2 Benefit Analysis Approach

The advantages of using P recycled via the Fe-WTR process include cost savings of sludge landfill, charges and fines on the discharge of wastewater with high P, TSS, and COD, and the direct saving costs of mining phosphorite rock from quarries. Additional benefits include the avoided environmental impacts of eutrophication and pollution, that often carry a social cost.

4. Results and Discussion

The production of 1 ton of P-Fe-WTR fertilizer, which has a P concentration of 6100 mg kg^{-1}, incurs the expenses detailed in Table 3. Given that Phosphorus is a recycled waste material and thus incurs no raw material cost, the overall production expense for 1 ton of this fertilizer alternative is estimated at €329, where the greatest contribution to this cost is attributed to the clarification pretreatment. Conversely, the LDH adsorbent represents a significant cost factor due to its synthetic nature; however, it is not only more expensive but also carries substantial environmental concerns. Thus, the financial outlay for creating 1 ton of P-LDH, with a P concentration of 7752 mg kg^{-1}, is considerably higher, totaling €3329 (Table 3).

The presented costs underscore the economic advantage of utilizing waste-derived adsorbents over synthetic alternatives. Moreover, the environmental impact, not directly accounted for in the cost but significant in a broader sustainability context, favors the use of recycled materials such as Fe-WTR, which align with the goals of a circular economy by minimizing waste and reducing reliance on non-renewable resources.

Table 3. Costs of production (per 1 ton of alternative P fertilizer). Data and Computations: Ganem et al., 2024 (unpublished data)

	Recycled WW-P [a] + recycled adsorbent	Recycled WW-P [a] + synthetic adsorbent	Commercial P Fertilizer
Variable costs (Euro)	Fe-WTR	LDH	
Absorbent materials [b]	0	3000	
Clarification wastewater pretreatment [c]	204	204	
Energy	125	125	
Total cost [d] of 1 ton fertilizer	**329**	**3329**	**50–64 [e]**

Note.

[a] Wastewater-P (WW-P) is recycled from dairy water after clarification with a nanocomposite.

[b] Market price reflects all the costs involved in supplying the product, including labor and transportation costs.

[c] Alternative clarification methods may be less costly per 111 m^3, required to prepare 1 ton of alternative adsorbent.

[d] Costs do not include transportation costs.

[e] ICL – Israeli Chemicals Ltd. The commercial fertilizer price is normalized to 1.397–1.776% P_2O_5 as a slow release fertilizer.

Table 4 details the aggregate saving in Israel, where the experiment of P recovery using Fe-WTR was conducted, as well as previous estimates of the detailed costs from other global studies. In Israel, P recovery through the Fe-WTR process can save approximately €40 euro per ton, while in Europe, this figure is markedly higher at €150 euro per ton (European Environment Agency, 2023). Avoidance of penalties for discharging P-laden wastewater, a central contributor to eutrophication and aquatic pollution, could represent a mitigation cost of around €500 euro per incident (Israeli Ministry of Environmental Protection, 2023). The reuse of P also diminishes reliance on quarry mining, with an attendant cost saving of €345 euro per ton and reduces the need for costlier commercial P fertilizers. Recycling P from organic sources, such as dairy wastewater, saves significant costs. This cyclical use of P not only economizes resources but also plays a pivotal role in reducing environmental damage, making it a dual boon of sustainability and economic sensibility.

The related quantified environmental benefits are primarily the cost implications of soil and water pollution by P. The ecological damage from P pollution in aquatic ecosystems is profound, threatening the survival of unique species and the ecological equilibrium. Assessing the monetary costs of reversing eutrophication – an outcome of P pollution – is complex due to fluctuating factors such as the intensity of contamination and the size of the affected water bodies. According to Dodds et al., (2009) and Martín-Hernándaez et al., (2021), the restoration expenses required to restore an aquatic ecosystem to its baseline state in the U.S. have been significant. Combined restoration costs range from €0.28 to €2.5 billion euro, with the loss in recreational value estimated between €0.34 and €1.07 billion euro annually. Notably, these figures do not consider the extensive time frames required for ecosystems to fully recover, often spanning years, nor do they account for the potential loss of biodiversity that may never be recovered. (Note 3)

Table 4. Alternative costs per 1 ton of alternative P fertilizer (P-Fe-WTR or P-LDH) and commercial fertilizers. The avoided cost is an indirect cost that society faces, given the alternative P production processes. These costs are saved when adopting a recycled P production process

	Cost (Euro)		References
	Alternative costs to recycled P production using Fe-WTR process (€ euro/ton)	Alternative costs of commercial P fertilizer valuation, based on previous studies	Data source
Iron sludge landfill – Israel	40		Israeli Ministry of Environmental Protection, (2023)
Wastewater discharge high in P, TSS [a,] and COD [b] Fines for discharge	500		Israeli Ministry of Environmental Protection, (2023)
Cost of 1 ton of phosphorite rock from a quarry	345	345	The World Bank, (2023)
Eutrophication and pollution [c]		0.28–2.5 billion	Dodds et al., (2009) Ayele and Atlabachew, (2021)
Total costs	**885**		

Notes:

[a] TSS, Total suspended solids.

[b] COD, Chemical oxygen demand.

[c] Eutrophication costs are site specific, depending on the size of the reservoir, the emission levels and the ecological footprint of the dairy wastewater.

Tables 3 and 4 indicate that the immediate financial returns from the use of the alternative P fertilizer investigated in this study are modest, but in the long-run, economic gains are significant. The adoption of a circular economy in production and recovery of Phosphorus is profitable and includes environmental benefits that outweigh alternative production of Phosphorus fertilizers. Anticipated price escalations, fueled by dwindling natural P reserves and the burgeoning global demand linked to population growth, are additional factors that have not been analyzed in this study, but strength the need to develop such circular production of Phosphorus and could increase the added value from such processes beyond the our estimates. Moreover, adopting the proposed circular approach to P fertilizer production not only presents an environmentally responsible practice but also a strategic economic advantage as market price continue to rise.

5. Conclusions

The cost-benefit analysis conducted to produce 1 ton of alternative P fertilizer, P-Fe-WTR, with 1.397% P_2O_5 composition, result in a significant cost reduction for phosphorus users, and thus provides a persuasive argument for its adoption. However, the financial implications extend beyond mere savings. The hefty fines imposed on the release of P-load wastewater, which may reach up to €500 euro per ton due to the potential for eutrophication and pollution, serve as a significant deterrent against conventional disposal methods. When juxtaposed with the costs of commercial fertilizers and quarry-extracted P, the P-Fe-WTR alternative emerges as a distinctly economical solution. The analysis presented also highlight the profound environmental merits of reducing eutrophication and mitigating pollution through the reuse of P-Fe-WTR. This sustainable pathway not only aligns with environmental priorities but also demonstrates clear economic incentives. In contrast to synthetic adsorbents, which are economically and environmentally costly, the study reveals that recycled adsorbents offer an economic and also an environmental advantage. The results presented could even improve over time with upscaling the volume of production using the recycled P-Fe-WTR processes.

By leveraging two distinct waste streams to create a valuable new resource, we reaffirm the viability of a circular economy in P fertilizer production. Projections indicate a sustained increase in the cost of commercial fertilizers, driven by higher demand for agricultural production. Geopolitical tensions and supply chain disruptions amplify this trend, potentially exacerbating price volatility. To navigate this landscape effectively, strategies focusing on resource efficiency, recycling, and sustainable P management are essential.

Despite these compelling findings, our research conclusions are subject to certain limitations that require further investigation. Firstly, the analysis focuses on cost-benefit metrics considering regional economic values and technologies, currently adopted in Israel and Europe. Changes in regional infrastructure, waste stream composition, and regulatory frameworks may influence the scalability and profitability of P-Fe-WTR production. Future research should explore regional variations to refine the global applicability of our findings. Furthermore, this study's environmental impact assessment incorporates the costs of eutrophication and pollution mitigation, relying on estimates from previous literature. Conducting a more comprehensive life-cycle analysis, including greenhouse gas emissions and energy consumption throughout the entire production chain, would offer a more complete perspective on the sustainability benefits of phosphorus recycling.

At last, while this study evaluates the economic and environmental benefits of P recycling, the long-term agronomic performance of P-Fe-WTR fertilizers in diverse soil and crop systems remains underexplored. Further experimental research is required to examine nutrient availability, uptake efficiency, and potential unintended impacts on soil health when using recycled P fertilizers at scale.

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Notes

Note 1. Capacity expansions to phosphate rock production that were expected to be completed by 2026 are ongoing in Brazil, Kazakhstan, Mexico, Morocco, and Russia. Significant new mining projects planned to be completed after 2027 are under development in Australia, Canada, Congo (Brazzaville), Guinea-Bissau, and Senegal. The new mines in Australia and Canada were planned to be primarily used for the manufacture of lithium-iron-phosphate battery cathode active material (US National Minerals Information Center, 2023).

Note 2. Various chemicals such as $FeCl_3$, $FeSO_4$, $Al_2(SO_4)_3$, and $CaCl_2$ can clarify wastewater but may unintentionally remove P, which is needed for adsorption (Ukiwe et al., 2013). However, the nanocomposite material 3% N/C 24 (an industrial material manufactured at the GES Your water treatment expert factory, Israel), used in this study, exclusively removes total suspended solids (TSS) while preserving nutrients such as P. Physical methods such as centrifugation are also available but yield low TSS removal, impacting P adsorption quality. Zohar and Forano, (2021) demonstrated almost twice the P adsorption on Fe-WTR and LDH adsorbents when clarified by N/C 24 compared to centrifugation.

Note 3. Using the recycled P material from sludges is not expected to increase soil salinity, since their sludges are usually washed with tap water in the desalination plant to avoid soil salinization.

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