Phosphorus recovery from domestic wastewater: A review of the institutional framework

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Abstract

Phosphorus (P) is an essential element for life that must be managed sustainably. The institutional framework for P recovery from wastewater includes policies, regulations, plans, and actions that promote the recovery, recycling, and safe use of this element, aimed at moving toward more sustainable nutrient management and environmental protection. This review analyzes the status of the institutional framework for P recovery from wastewater in different countries around the world. Europe is the continent where the most progress has been made in terms of legislation. Countries such as Germany, the Netherlands, Austria, and Denmark have already implemented policies and regulations that promote environmental protection, as well as P recovery and reuse. In other parts of the world, such as the United States, China, and Japan, there have also been significant advances in promoting the closure of the P cycle, with the implementation of advanced recovery technologies in wastewater treatment plants and regional/national action plans. By contrast, in Latin America there has been little progress in P treatment and recovery, with a weak regulatory framework, unclear goals, and insufficient allocation of techno-economic resources. In this context, it is necessary to reinforce the comprehensive institutional framework, which covers technological aspects, economic incentives, political agreements, and regulations, to promote the sustainable management of this valuable resource.

1 Introduction

Phosphorus (P) is an essential element for life responsible for storage of genetic information and intracellular energy transfer in metabolic processes, as it is a component of phospholipid molecules in the cell membrane and molecules such as nucleic acids (DNA and RNA) and adenosine tri-, di-, or mono-phosphate (ATP, ADP or AMP) (Elser, 2012). However, despite its importance, P has no substitute, which makes it a fundamental resource for the development and functioning of terrestrial and aquatic ecosystems (Desmidt et al., 2015). P was discovered in the 17th century and Albino found it in plants in 1688 (Figure 1). This achievement led to the establishment of British patents for the manufacture of fertilizers from sulfuric acid and bones and, subsequently, the world's first fertilizer factory was established in Deptford, England (Corbridge, 2013). Mined phosphate rock is currently the main source of P, but its limited availability poses a significant challenge. Since the 19th century phosphate rock has been overexploited to produce fertilizers, thus putting increasing pressure on existing reserves, which could be exhausted in the coming decades (Cordell et al., 2009; Withers et al., 2015). The intensification of chemical fertilizer use allowed for better crop yields, driving the Green Revolution during the 1960s (Kok et al., 2018).

The intensive supply of P to the soil has altered the global cycle of this element by mobilizing up to four times the natural level of P from phosphate rock into the environment (Cordell and White, 2014). Thus, a large part of this P, which is not assimilated by crops, will be mobilized by infiltration and runoff, reaching surface water. Such inputs, together with discharges of insufficiently treated wastewater, generate anthropogenic eutrophication (Kok et al., 2018).

In the mid-20th century, there was a rapid increase in P pollution in water, with serious consequences for human health, ecosystems, and the economy. Therefore, more sophisticated wastewater treatment processes were implemented, including secondary treatment to reduce biochemical oxygen demand (BOD) and tertiary treatment to remove P (Ashley et al., 2011). For example, in the United States, wastewater treatment plants (WWTPs) have changed since the 1960s; the proportion of WWTPs based on a primary treatment (with the capacity to remove between 5% and 10% of P) has decreased until almost disappearing, while WWTPs with tertiary treatment (with the capacity to remove up to 99% of P) had increased to 25% of the total as of 2000 (Litke, 1999). In addition, in 1982 the Organization for Economic Cooperation and Development (OECD) established the trophic state classification, designed to evaluate water quality in terms of nutrients, improving the management and protection of water resources worldwide (OECD, 2012).

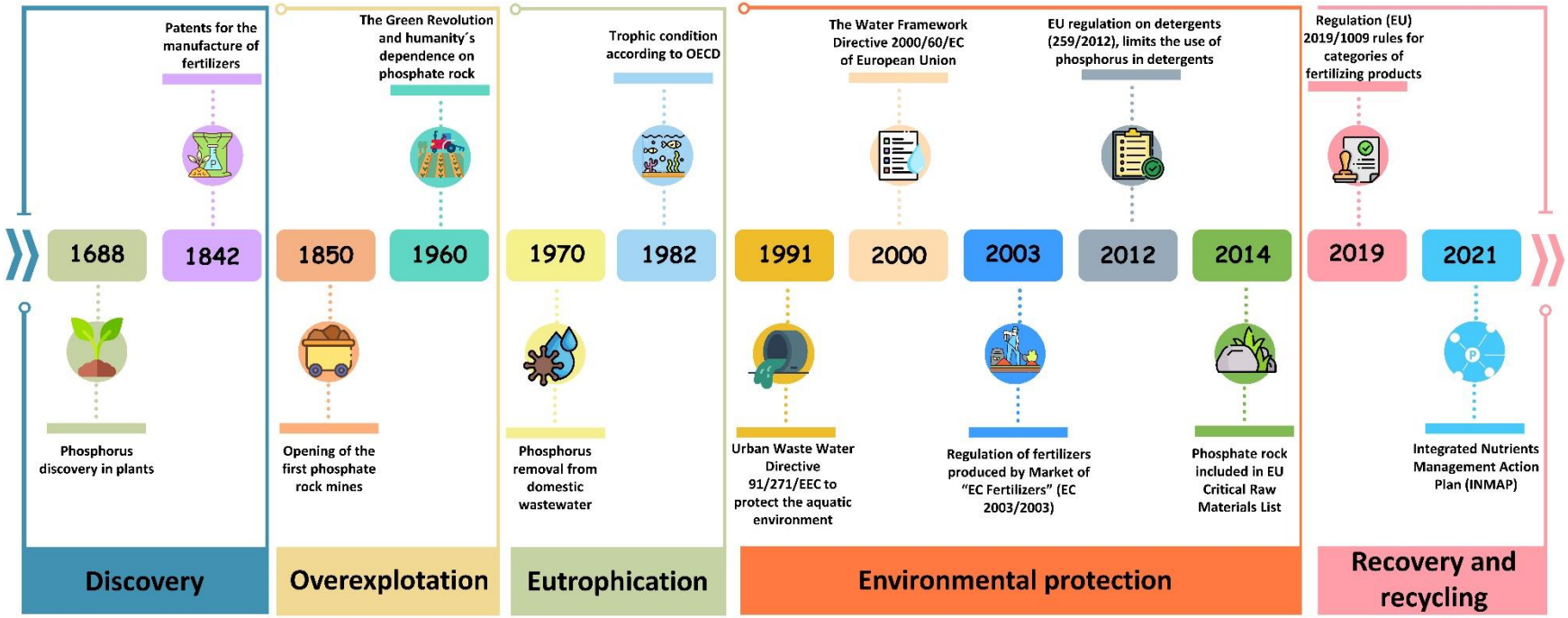

Figure 1. Timeline of the history of phosphorus (P), from its discovery to its recovery and recycling.

During the 1990s and 2000s, governments and international organizations began to take environmental protection measures aimed at preventing and controlling eutrophication, preserving farmland, and treating wastewater. At the European Union (EU) level, these measures have involved the entry into force of directives such as Directive 91/271/EEC (EC, 1991), which establishes a framework for wastewater treatment, and the Water Framework Directive (2000/60/EC) (EPC, 2000), which specifies policy guidelines for the protection and sustainable management of water resources. In addition, other regulations were established in the following years, e.g., regarding the use of P in detergents to reduce the quantity of P released into the environment via wastewater (Regulation 259/2012) (EPC, 2012). Another important milestone was the official inclusion, in 2014, of phosphate rock and P in the critical raw materials list (EC, 2023) because of the EU's high dependency on foreign sources of P and the need to secure its own sources.

In the 21st century, perceptions of P have changed, with it going from being considered a pollutant to being recognized as a scarce resource worldwide (Ashley et al., 2011). Therefore, the current approach in wastewater treatment proposes a paradigm shift, with P moving from "waste" to "valuable raw material" (De Boer et al., 2018). This new situation entails the extraction of P from wastewater for its subsequent reuse in fertilizer production, thereby allowing cycle closure. In this context, initiatives such as Regulation (EU) 2019/1009 (EPC, 2019) emerge, which seeks to ensure the safe use and marketing of EU fertilizer products. This approach proposes the reuse of recovered P, reducing dependence on imports, thereby guaranteeing a sustainable, stable supply of P for agriculture and other key sectors of the EU economy. In addition, the European Sustainable Phosphorous Platform (ESPP), a collaborative initiative that aims to foster alliances and sustainable practices related to P recycling, has been established (ESPP, 2017).

Nonetheless, the efforts mentioned above are clearly geared toward a European-level institutional framework, leaving aside other world regions. Experiences in the United States and East Asia (China and Japan) have mostly focused on the implementation of P recovery technologies and sludge reuse, but legal policies are comparatively scarce and there are no approved regulations requiring P recycling in the wastewater treatment sector (Nättorp et al., 2019; Shaddel et al., 2019). Meanwhile, in South America and Africa there is a lack of wastewater treatment facilities, and the absence of economic incentives has led to dumping or direct discharge into the environment being the most common practices (Shaddel et al., 2019). This reality shows the need for a holistic approach when managing the closure of the P loop, which must focus not only on treatment technology, but also on regulatory, economic, environmental, and public health aspects. Therefore, the information analyzed in this review provides valuable tools for policy makers to design effective strategies to address the problems related to P shortages and contamination of water resources.

2 Institutional framework for the sustainable management of phosphorus

The current unsustainable use of P worldwide calls for a cycle-closure strategy for the recovery and reuse of this element. There is no single solution to resolve the P problem, but there are several waste streams (wastewater, animal-derived waste streams, meat, and bone meal waste, etc.) and loss streams (infiltration and runoff) from which phosphate can be recovered and used (Sarvajayakesavalu et al., 2018). The purpose of these

efforts must be to create a circular and sustainable P management system, reducing reliance on the extraction of finite phosphate minerals. Human production systems need to be redefined and redesigned according to the corresponding institutional framework, which refers to the set of laws, regulations, policies, agreements, organizations, and processes that make up the institutional system (Ahlström and Cornell, 2018). This concept is applicable to the sustainable management of P and should involve wastewater treatment alternatives aimed at recovering this nutrient, the reuse of products with high P content, the establishment of agreements for the fertilizer market, and limits on its application in agriculture. Thus, these alternatives reduce P losses and ensuring environmental safety and public health protection (Figure 2).

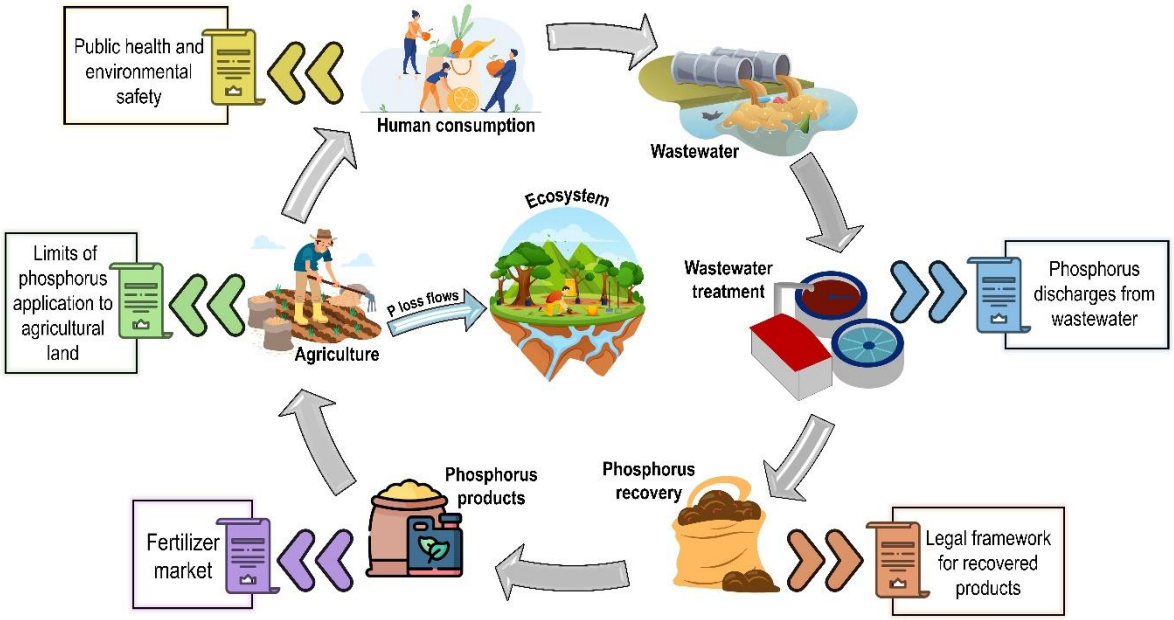

Figure 2. Schema of the institutional framework for the recovery of phosphorus (P) from wastewater, aimed at cycle closure. The institutional framework establishes legal and regulatory bases for P discharges and recovery processes, the fertilizer market, and fertilizer application, reducing losses, and ensuring environmental safety and public health.

The legal framework must include incentives and public policies that promote P recovery in treatment plants, such as subsidies, financial support, and fiscal incentives (De Boer et al., 2018; Nanda and Kansal, 2021). In this regard, one of the main barriers to tackle is the treatment cost, since many waste-derived fertilizers are not competitive on the market given the high cost of the recovery process. In addition, the existence of a consolidated market for the recovered products is essential. This circumstance will facilitate P recovery initiatives and support a safe, regulated transition toward more sustainable nutrient management practices (Barquet et al., 2020). The use of P in agriculture is a point that is not often discussed in the literature. The implementation of practices and guidelines is essential not only to reduce P losses through infiltration and runoff, but also to ensure the safety of commercial products. In this case, these products must provide bioavailable nutrients for crop production and meet quality standards for protecting human health.

Social aspects and environmental education play a crucial role in the acceptance of the institutional framework. It is vital to build confidence among farmers in and acceptance among the population of new fertilizers derived from wastewater treatment. Furthermore, it is necessary to raise awareness of the market for phosphate fertilizers derived from secondary raw materials and interest in using them (Huygens and Saveyn, 2018). To this end, a new and broader understanding of the environmental and economic benefits of these practices must be promoted by providing information about the measures and appropriate protocols for the effective, safe, and responsible use of these fertilizers, as well as the associated risks.

In general terms, the institutional framework establishes the implementation of various measures, in close collaboration with all involved parties and relevant stakeholders, to promote P recovery and establish a market for the recovered products. The involved stakeholders include governments, research institutions, the sanitation and fertilizer sectors, non-governmental organizations, farmers, agricultural producers, and the general population. However, there is often a lack of communication, coordination, and structure among the ministries, departments, and organizations involved. To foster common interests, it is crucial to work together, with a transdisciplinary approach, addressing all aspects related to P recovery in order to create a sustainable framework for this resource (Nanda and Kansal, 2021). In addition, the implementation of appropriate policies is essential for public health security and environmental protection. These measures work together to provide security and promote sustainability in the use of P resources.

2.1 Phosphorus as a pollutant in wastewater treatment

One of the main driving forces of the interest in P recovery from wastewater was the increase in water pollution levels, which encouraged the implementation of legal regulations that established treatment requirements and standards (Sarvajayakesavalu et al., 2018). In this sense, government entities are responsible for developing and enforcing compliance with these rules and regulations (Schellenberg et al., 2020). However, although many countries have adopted regulations based on the properties of treated wastewater, most of them focus on organic matter and suspended solids. According to the World Health Organization (WHO, 2018), only 75% of national discharge regulations include P as one of the pollutants to be monitored.

Standards for P discharge aim to protect and preserve the quality of the receiving water bodies, recognizing the importance of P in eutrophication. Typically, a maximum allowable concentration of total phosphorus (TP) or orthophosphate (PO_4) in the treated water before discharge is established, with limits in terms of the P load sometimes imposed (Preisner et al., 2020; Schellenberg et al., 2020). Table 1 summarizes the treated wastewater discharge standards in various countries around the world. These standards are usually within the scope of environmental laws, protection against pollution of natural areas, and natural resource management. However, some countries such as the United States, Costa Rica, Uruguay, Switzerland, and Germany, as well as those of the EU, have specific laws for the protection of the water resources, which place greater emphasis on water preservation and management.

Phosphorus discharge limits range from 0.005 to 15 mg/L and can vary depending on the size of the WWTP, environmental or geographic characteristics, the origin and use of the wastewater, and the assimilation capacity

of the receiving water body. This last characteristic refers to the maximum amount of pollution that can be diluted or degraded naturally without affecting the predefined use of water (Schellenberg et al., 2020). Thus, countries such as the United States, Canada, Mexico, Peru, Chile, Dubai, and New Zealand impose P discharge limits according to the characteristics of the receiving water body, with the most stringent limits for lentic systems (up to 5 mg/L), followed by lotic systems (up to 15 mg/L), and, finally, seawater (a limit of 15 mg/L).

In Latin America regulations are less demanding, focusing on treated wastewater discharges without considering the classification of the water bodies. This is the case of countries such as Nicaragua, Costa Rica, Colombia, Ecuador, Uruguay, and Bolivia (Government of Bolivia, 1995; Government of Uruguay, 1979; Government of Colombia, 2015; Government of Ecuador, 2015; AECID, 2021). However, countries such as Uruguay, Peru, and Bolivia have established environmental quality levels based on water use type. In general, the classification is divided into three or four categories, with the most demanding regulations applied to water for domestic and human consumption uses (Government of Bolivia 1995; Government of Uruguay, 1979; Government of Perú, 2017). Peru is one of the Latin American countries with the most complete effluent regulations, categorized by water use and type of receiving water body (Government of Perú, 2017). Meanwhile, Colombian regulations do not establish specific P concentration limits for discharges, and only require analysis and reporting of the results (Government of Colombia, 2015).

The EU and countries such as United States, Switzerland, and China include the protection of eutrophication-sensitive water bodies in their strategies to reduce environmental impacts. This allows the definition of stringent P discharge standards ranging from 0.1 to 2 mg P/L. Some EU member countries such as Germany, Denmark, Sweden, and Switzerland promote local and regional standards considering other properties in addition to those established by the EU. Germany has national effluent management regulations that consider the water quality and characteristics of the receiving water bodies (Government of Germany, 2004). In Sweden, it has been specified that all water bodies, including coastal areas, are sensitive to P discharges (Åkerblom et al., 2020). Similarly, in Switzerland, the Water Protection Ordinance (WPO) implemented in 1998, limits the discharge of orthophosphate into sensitive water bodies such as lakes and watercourses, as well as from WWTPs with capacities greater than 10000 population equivalent (PE) (Preisner et al., 2020).

193 **Table 1.** Standards for phosphorus discharge limits in treated wastewater.

Continent	Country	Law	Standard	Classification	Type of water	Limits (mg TP/L)	References
Asia	China	Ministry of Environmental Protection of the Peoples Republic of China (1984)	(GB18918-2002) Discharge standard of pollutants for municipal wastewater treatment plants	-	Sensitive areas Standard	0.5 1	Zhang et al. (2023)
	India	Environment Protection Act (1986)	National Green Tribunal order, 2019	-	Lotic	1	Schellenberg et al. (2020)
	Japan	Water Pollution Control Law (1970)	Water Environment Quality Standards (EQS)/ 1991	Environmental Protection	Lake Sea area	0.005 - 0.1 0.02 - 0.09	Wako (2012)
	United Arab Emirates (Dubai)	Federal Law N° (24/1999) Protection and Development of the Environment	Water Environment Regulation EN-5.0/2018	-	Harbor area Lotic Seawater	2 0.033 0.016	Government of Dubai (2018)
Europe	Denmark	Environmental Protection Act N° 698 (1998)	Guidelines N°42/1988, national standards for discharges into watercourses, lakes, or the sea	-	Sensitive areas	0.4	Vind (2017)
	European Union (EU)	Council Resolution (88/C 209/02) Protection of the North Sea and of other waters	Directive 91/271/EEC concerning urban wastewater treatment	From 10000 to 100000 PE > 100000 PE	Sensitive areas	2 1	EEC (1991)
	Germany	Federal Water Law (WHG) No. 59/1957	Ordinance on the requirements for the discharge of wastewater into water (AbwV), 1997	From 10000 to 100000 PE > 100000 PE	Sensitive areas	2 1	Government of Germany (2004)
	Sweden	Environmental Protection Act (1969:387) / Swedish Environmental Code 61:2000	Swedish EPA regulations (NFS 2016: 6)	> 2000 PE	Sensitive areas	0.5	Åkerblom et al. (2020)
	Switzerland	Federal Water Protection Act 1991	Water Protection Ordinance 814.201, 1998	> 10000 PE	Sensitive areas	0.8	Government of Switzerland (1998)
North America	Canada	Environmental Management Act (2003)	Municipal wastewater, B.C. Reg. 87/2012	50 m^3/d	Lentic Lotic	1 1	Government of Canada (2012)
	Costa Rica	Water Law No. 276	Decree Nº 33601/2007-MINAE-S ─ Wastewater Discharge and Reuse Regulation	-	Inland surface water	8.2	AECID (2021)

	Mexico	National Water Law (1992)	Mexican Official Standard NOM-001-SEMARNAT-2021	-	Lentic Lotic Seawater	5 15 15	Government of Mexico (2021)
	Nicaragua	Law N° 217-General Law on the Environment and Natural Resources	Decree Nº 21/2017 – Regulation establishing the provisions for the discharge of wastewater.	-	Inland surface water	10	AECID (2021)
	United States	Clean Water Act (1972)	National Pollutant Discharge Elimination System (NPDES), 2012	Sensitive areas	Lentic Lotic	0.1 1	USEPA (2012)
Oceania	Australia	Environmental Protection Act of Victoria 1970	Industrial Waste Environmental Protection Regulations / 2019	-	Inland surface water	1	Government of Australia (2019)
	New Zealand	Resource Management Act 1991	National Environmental Standards for Wastewater (NES Wastewater), 2014	Sensitive areas	Inland surface water Lotic Lentic	1 0.2 0.4	Johnson and Feise-Preston (2009)
South America	Bolivia	Environmental Law N° 1333/1992	Supreme Decree N° 24176/1995: Water Contamination Regulations	4 Classes	Inland surface water	0.4-1	Government of Bolivia (1995)
	Chile	Law 19.300/94 General Bases of the Environment / Sanitarian Code / Law 18.902 Superintendent of Sanitary Services	Primary Water Emission Standards D.S. MINSEGPRES N°90/00	-	Lotic without dilution Lotic with dilution Lentic Seawater	10 15 2 5	Government of Chile (2000)
	Colombia	Law 99/1993 - Ministry of the Environment and Sustainable Development	Resolution 631/2015	-	Inland surface water	Analysis and Reporting	Government of Colombia (2015)
	Ecuador	Agreement N° 061– Secondary legislation of the Ministry of the Environment	Agreement N°.97/2015 – Environmental quality standard and effluent discharge to water resources	-	Inland surface water	10	Government of Ecuador (2015)
	Peru	Law N° 28.611/2007 General Environment Act	Supreme Decree N° 004/2017 – MINAM: Approves Environmental Quality Standards (EQS) for water and establishes complementary provisions	4 Classes	Lentic Lotic Seawater	0.035 0.05 0.6-0.1	Government of Peru (2017)

	Uruguay	Uruguay Water Code 1978	Decree N° 253/979 / 1979 Approval of regulations to prevent environmental pollution through water control	4 Classes	Inland surface water	5	Government of Uruguay (1979)

194 PE: Population Equivalent (1 PE = 60 g BOD_5/d); BOD_5: 5-day Biochemical Oxygen Demand.

195 Lentic ecosystem: entails a body of standing water, such as a lake, pond, reservoir, or lagoon.

196 Lotic ecosystem: any kind of moving water such as a river, stream, or canal.

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198 The most stringent regulations for P discharge in WWTPs are found in countries such as Denmark and New
199 Zealand. These countries stand out for their stringent treatment standards, which impose specific design,
200 operation, and maintenance requirements for the implemented technologies in order to guarantee effective P
201 removal from wastewater (COWI, 2001). Similarly, according to its current regulations, Japan also promotes
202 intensive wastewater treatment in industrial and municipal facilities prior to water discharge to satisfy
203 environmental quality standards (Wako, 2012). In China, the National Environmental Protection Action Plan
204 was implemented in 2014 to better control of water pollution levels, which were relatively high (Zhang et al.,
205 2023). In addition, the government of Dubai assumed the importance in 2017 under the UAE Water Security
206 Strategy 2036 (Government of Dubai 2018). In these nations, a new ecosystem approach can be observed, which
207 is characterized by consideration of ecological properties in order to manage and preserve water resources with
208 a comprehensive and sustainable perspective of water.

209 A disadvantage of low discharge limits is the resulting need to incorporate of tertiary treatment into WWTPs,
210 which leads to high treatment costs. Therefore, restricting dischargers' P loads will inevitably exert a significant
211 financial burden on municipalities. This is reflected in developing Latin American countries, where the lack of
212 advanced technologies shows the low quality of the water and, sometimes, the release of untreated wastewater
213 into the receiving water bodies. In contrast, Denmark stands out as one of the pioneering countries in the
214 implementation of policies to prevent eutrophication, promoting the adoption of advanced technologies in
215 wastewater treatment, including tertiary treatment for all WWTPs (< 5000 PE) (COWI, 2001). These initiatives
216 were supported by uniform economic measures nationwide, such as the so-called “polluter pays principle” tax,
217 which obligates WWTPs to pay a rate based on pollutant type and the quantity discharged above the amount
218 stipulated by the standard. These rates are based on organic matter parameters, and currently (2023) the P tax
219 is approximately equivalent to 26 USD/kg P (Vind, 2017).

220 The imposition of strict standards for P discharges, as in Europe, Asian countries, and the United States,
221 puts pressure on government entities in charge of water treatment, incentivizing them to improve technologies,
222 policies, and processes. This intensified focus on treatment translates into increased attention on P recovery
223 from wastewater given the global decline in high-quality supplies (Sarvajayakesavalu et al., 2018). These
224 policies push identities and treatment companies to adopt new proactive approaches to recovery. However, the
225 lack of adequate infrastructure and a strong institutional framework can hinder this process. The deficiency of
226 economic incentives and the high associated costs are key factors that further explain the low recovery of P. To
227 overcome these challenges, it is essential to identify opportunities for improvements and develop economic
228 plans that drive the adoption of long-term sustainable practices in P management (Preisner et al., 2020).

229 **2.2 Phosphorus as a resource to be recovered from wastewater**

230 The standards applied to WWTPs require only the removal of P, without addressing its recovery and reuse
231 (Garske et al., 2020). However, wastewater is a secondary source of P and has already been called “the untapped
232 resource” (Huygens and Saveyn, 2018). In WWTPs, P can be recovered using different technologies (i.e., based
233 on physical, chemical, or biological mechanisms), which makes them ideal places for avoiding P losses (Vučić

et al., 2021). In such facilities, processes aimed at P recovery can be combined with other existing processes for integrated wastewater treatment (Carrillo et al., 2020; Magrí et al., 2020).

To date, few countries have taken concrete action (i.e., promoted environmental policies, strategies, or commercial models) to boost P recovery in WWTPs. The number of large-scale facilities incorporating P recovery has approximately tripled in the last decade, from 25 units in 2010 to 79 units in 2018. Europe stands out as the leader in the number of large-scale facilities (50 units), exceeding the rest of the world (29 units). Germany and the Netherlands are among the main countries that address P treatment and recovery. The United States and Canada follow in the ranking, with 15 units, while Asia (with Japan at the top) has 13 plants installed (Kabbe, 2017). Finally, Australia also has a P-recovery facility. Details of each WWTP, including city, year of implementation, type of technology, and operational performance, are described in Table S1.

P is typically recovered from wastewater via precipitation of calcium phosphate (CaP) (e.g., hydroxyapatite (HAP)) or magnesium phosphate (MgP) (e.g., struvite (MAP)) and it can be recovered from liquid streams (wastewater) and solid streams (sewage sludge) (Carrillo et al., 2020). In approximate terms, reachable recovery efficiencies range from 10% to 40% when treating wastewater. However, these values increase between 40% to 90% when handling sewage sludge, and they are above 60-100% for sewage sludge ash. The most technologies for large-scale P recovery currently focus on the treatment of liquid streams (wastewater, digested sludge (dissolved P), digester supernatant, secondary treated effluent), accounting for 59%, followed by sewage sludge with 31% and sewage sludge ash with 10%. Countries such as Germany and Japan stand out in the recovery of P from sewage sludge ash (see Table S1) (Egle et al., 2015; Kabbe, 2017; Shaddel et al., 2019; Nättorp et al., 2019).

Table 2 shows the regulatory framework for P recovery in different countries worldwide. An incipient regulation on P recovery from wastewater arose largely in the EU, where laws concerning this activity can be found at community and national levels (Sichler et al., 2022). EU legislation, exemplified by Council Directive 86/278/EEC (EEC, 1986), requires sludge treatment before agricultural use and prohibits untreated sludge application on farmland unless injected or incorporated into the soil. As part of the progress on new sustainable development, the "European Green Deal" includes a "Circular Economy Action Plan" that focuses on water reuse in agriculture and integrated nutrient management. Furthermore, the Waste Framework Directive (2008/98/EC) introduces waste management principles, including the "polluter pays principle" and "extended producer responsibility scheme" (EPC, 2008).

At the national level, some laws stand out for establishing an advanced institutional and regulatory framework for P recovery. Germany, the Netherlands, and Switzerland have laws that promote the recovery of P from sewage sludge and sludge ash, while Denmark and Austria prioritize P recovery from liquid streams.

267 **Table 2.** Regulatory framework for phosphorus (P) recovery from wastewater.

Country	Law	Standard	Legally binding	Institution	Implementation deadlines	Content highlights	References
EU	European Union legal framework -	Directive 86/278/EEC on the protection of the environment and soil when sewage sludge is used in agriculture Waste Framework Directive (2008/98/EC) Closing the loop - Action plan for the Circular Economy (2020)	No	European Commission (EC)	- 2020	Requires that sludge be used in a manner that considers the nutrient needs of plants and does not deteriorate the quality of soil, surface water, or groundwater. EU waste management, including waste prevention, reuse, recycling, and recovery. Promotes sustainability and resource efficiency and provides guidance and support to encourage their implementation across Europe.	EEC (1986) EPC (2008) EC (2015)
Austria		Federal waste management plan (2017)	No	Municipal wastewater treatment plants; Federal Ministry of Agriculture, Forestry, Environment and Water Management	65-80% by 2030	Phosphorus recovery from wastewater, sludge water, or sewage sludge, with a rate of at least 45% by weight, relative to the input of the treatment plant.	Government of Austria, (2017)
Denmark		Resource plan for waste management 2013-2018	No	Public policy level	50% to 80% by 2018	Eighty percent of the phosphorus in sewage sludge and industrial sludge will be recycled, using the phosphorus in the ash from sludge incineration as a fertilizer or by spreading it on farmland.	Government of Denmark (2014)
Germany	Federal Water Act to Promote Circular Economy and Safeguard the Environmentally	Wastewater Ordinance, Sewage Sludge Ordinance (2017)	Yes	Municipal wastewater treatment plants	2029	WWTPs must recover phosphorus if in sewage sludge or ash containing more than 20 g/kg DM.	Sichler et al. (2022)

	Compatible Management of Waste (2012)						
Netherlands		Environmental Impact Assessment Directive; Industrial Emissions Directive (2014) (EU regulations); Dutch fertilizer law	Yes		25% as a long-term goal	The fertilizer law notes the goal of 25% of fertilizers being made from recovered P, although without specifying targets.	Government of the Netherlands (2014)
Switzerland	Environmental Protection Act of 7 October 1983; Waters Protection Act of 24 January 1991	Ordinance on the avoidance and the disposal of waste (2015)	Yes	Municipal wastewater treatment plants; Cantons; Federal Office for the Environment	2026	Phosphorus-rich waste must be recovered from wastewater, sludge, or ash, which must be recycled and be free of regulated pollutants.	Government of Switzerland (2015)

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Countries such as Germany and the Netherlands are pioneers in this area, marked by support in the regulatory framework of the EU. Germany has enacted an ordinance to reform sewage sludge management. This federal regulation specifically requires municipal water treatment companies to recycle P contained in sludge. A period of 12 years is established to implement measures and plans, with a focus on achieving the highest quality standards (EC, 2020; Government of Germany, 2017). In the Netherlands the regulation is mainly shaped by its Environmental Impact Assessment Directive and Industrial Emissions Directive, as well as the internal development of Dutch fertilizer regulations. As of 2014 in the Netherlands, around 0.210 kt of P were recovered per year in the form of struvite. Over time, it is expected that 2.5 kt of P could be recovered in the form of struvite. This goal, unlike proposals in other legislation, is not associated with a compliance target (Government of the Netherlands, 2014).

In Austria, the Federal Waste Management Plan of 2017 focuses on small-scale reuse of P from sewage sludge from agricultural wastewater, with a reuse target of 65% to 80% by 2030. P recovery applies to WWTPs with more than 0.8 g of P per PE and year (Government of Austria, 2017; Sichler et al., 2022). Meanwhile, in Switzerland environmental regulations address the reuse of water and nutrients, including the recovery of P according to the Ordinance on the Avoidance and Disposal of Waste of 2015, amended in 2018 (Government of Switzerland, 1983, 1991). This ordinance requires the recovery of 6 kt of P per year of sewage sludge or ashes obtained from its incineration, with mandatory compliance as of January 1, 2026. (Government of Switzerland, 2015; Nättorp et al., 2019). In Denmark, meanwhile, the 2013-2018 Waste Plan provides for measures and targets to increase P recovery from 50% to 80% during this period. This objective is achieved through grants for research and development, technological testing, life-cycle monitoring, and socioeconomic analyses of the use of this waste, as well as the possible creation of "P banks" to separate and store the ashes resulting from the incineration of sewage sludge. In addition, a public-private dialogue has been initiated with fertilizer manufacturers to discuss the use of recycled P as fertilizer (Government of Denmark, 2014).

Other countries such as Belgium and France, despite not having specific regulations on P recovery, have action plans. In Belgium in 2014 the "Sustainable management of (secondary) biomass flows" plan (2015-2020) was published; it provides a guiding and inspiring framework for the sustainable and efficient use of biomass waste for the next five years, including nutrient recovery and biomass waste valorization in agriculture and animal feeding. In France, the government has called for an increase in nutrient recycling through its recent reform "Agriculture – Innovation 2025," the goal of which is to increase the carbon content of soil to improve its fertility and face climate change (Kabbe, 2017; Kabbe et al., 2017).

It is important to note that, although there is no specific national standard or regulation on P recovery from wastewater in Asia, some companies and pilot projects have been working on technologies and practices for nutrient recovery. Japan has over ten large-scale P recovery plants in operation; however, rather than being an obligation, P recycling is considered a secondary or cost-saving objective due to alternative undesired precipitation in pipes and other equipment in WWTPs. In addition, Japan has been promoting a policy to recycle P, supported by research on material flow analysis, social life-cycle assessment, interested party analysis, and

the creation of the Phosphorus Recycling Promotion Council of Japan in 2008 (Nättorp et al., 2019). In China initiatives more focused on nutrient recovery and promotion of a circular economy in the wastewater treatment sector have been developed. Such practices and technologies could provide useful information and experience for future legal considerations related to P recovery from wastewater in these countries or others (Shaddel et al., 2019).

2.3 Phosphorus as a recovered product

In the circular economy paradigm, P can be recovered from wastewater as a valuable product (e.g., precipitated phosphate salt (MgP, CaP, or FeP), sludge, P-rich ashes and slags, or P-rich pyrolysis and gasification materials (biochar)). These recovered P-rich products have specific particularities but are considered a significant category of secondary raw materials for agriculture (Huygens and Saveyn, 2018; Magrí et al., 2020). Struvite is the most frequently recovered product, accounting for 74% of the market, with the Pearl® (OSTARA) (18%), AirPrex® (10%), and NuReSys® (13%) technologies being the most widely used (see Supplementary Materials, Table S1) (Egle et al., 2015; Kabbe, 2017; Shaddel et al., 2019; Muys et al., 2021). However, to be used as fertilizers, recovered P products must meet agricultural, environmental, and health quality criteria in accordance with legislation on fertilizers (Morgenschweis et al., 2015).

Table 3 presents some regulations governing recovered P products, quality requirements, and their application in agriculture. Current European legislation is the most advanced among all nations; however, it is quite fragmented. WWTPs that promote waste recovery, valorization, or recycling are subject to the Environmental Impact Directive (EIA) (2011/92/EU), Industrial Emissions Directive (IED) (2010/75/EU), and Waste Framework Directive (WFD) (2008/98/EC) (EPC, 2008, 2010, 2011; Hukari et al., 2016). It is important to keep in mind that the application of a specific directive for P recovery projects can vary according to the specific laws and regulations in each EU member country.

All companies must acquire permits for their P recovery installations. Currently, most WWTPs are classified as “waste management” facilities and must follow stricter and more costly rules than chemical fertilizer companies. Consequently, WWTPs often label their recovered P as “waste” rather than fertilizer within the circular economy framework, leading to legislative complications (De Boer et al., 2018; Jupp et al., 2021). In addition, the WFD defines key concepts such as waste valorization and elimination and when it ceases to be waste, essential terms for P management, distinguishing P waste, by-products, and secondary raw materials (Kabbe et al., 2017). If the WWTP produces a fertilizer (product), it must be identified as a "fertilizer producer," which requires verification and relevant information on treatment processes (EPC, 2019; Hukari et al., 2016).

336 **Table 3**. Regulatory framework for recovered Phosphorus (P) products and their application in agriculture.

Country	Standard	Institution	Applies/Regulates	Contents Highlights	Quality criteria	References
EU	Sewage Sludge Directive – 86/278/EEC	European Commission	Agricultural application of sewage sludge	Prohibits the use of untreated sludge on arable land; regulates contaminants; sets restrictive EU-wide standards for soil and human health protection.	-Dry and organic matter, pH, nitrogen and phosphorus, cadmium, copper, nickel, lead, zinc, mercury, chromium	EEC (1986)
	Fertilizer Regulation - 2003/2003/EC - modified by Regulation (EU) 2019/1009	European Commission	Fertilizers — chemical compounds that provide nutrients to plants	Introduces limits for toxic contaminants and seven categories of fertilizer products and fertilizers, such as: organic fertilizers and organo-mineral fertilizers, soil amendments, inhibitors, plant biostimulants, and growing substrates. List expanded by adding precipitated phosphate salts and derivatives ("struvite") in July 2022.	Micronutrients (boron, cobalt, iron, manganese, molybdenum) and macronutrients (nitrogen, phosphorus), pH, conductivity, heavy metals (cadmium, chromium, lead, mercury, nickel, arsenic), microorganisms, and organic carbon.	EPC (2019)
	Waste Framework Directive (WFD) 2008/98/EC	European Commission	Waste valorization	Explains when a waste ceases to be a waste and becomes a secondary raw material and how to distinguish between wastes and by-products; Classification of the production WWTP as a "waste management" operation	n.a	EPC (2008)
	Environmental Impact Assessment (EIA) Directive 2011/92/EU	European Commission	Fertilizer manufacturers	If the waste is used as raw material for fertilizer production	n.a	EPC (2011)
		European Commission	Wastewater treatment plant	An EIA is required for waste disposal facilities that incinerate, chemically treat, or deposit hazardous waste in landfills		
	Industrial Emissions Directive (IED), Directive 2010/75/EU	European Commission	Fertilizer manufacturing installations	Grants permits for waste recovery facilities and obliges operators to submit relevant information on their processes and plants to the authorities.	Limits emissions and waste related to fertilizer production	EPC (2010)

Germany	German Fertilizer Ordinance (DüV) 2017	Federal Ministry of Agriculture and Food	Fertilizers	Transposes or implements legal acts of the European Community in relation to trade or application of fertilizers.	Amount and bioavailability of nutrients (nitrogen and phosphorus), heavy metals, persistent organic compounds (POCs), pathogens, chemical contaminants	Government of Germany (2017)
			Efficient phosphorus fertilization	Good professional practices, adjusting the type, amount, and timing of fertilizer application, and restriction of P fertilization in soil according to plant and soil requirements.		
Netherlands	Fertilizer Law 2015	Foundation for Applied Research Water Management (STOWA)	Fertilizers Act (Meststoffenwet)	Requirements for marketing, labeling, and quality certification of fertilizers used in agriculture.	Agricultural compounds (including N and P levels), heavy metals, organic micro-pollutants, other organic micro-pollutants, pathogens	Morgenschweis et al. (2015)
			Decree and Fertilizers Act (Implementation)	Covers aspects such as fertilizer composition, permissible contaminant limits, application practices and quality control procedures.		
Switzerland	Ordinance on the Reduction of Risks relating to the Use of Certain Particularly Dangerous Substances, Preparations, and Articles	The Swiss Federal Council	Fertilizer: Phosphorus-rich waste	Terms on fertilizers and cropland surfaces; restricts the use of dangerous substances. Organic fertilizers, recycling fertilizers with the exception of mineral recycling fertilizers and farm manure	Inert contaminants, heavy metals: cadmium, copper, nickel, lead, zinc, mercury, arsenic, chromium, vanadium. Polycyclic aromatic hydrocarbons (PAHs), dioxins (PCDDs), and furans (PCDFs), polychlorinated biphenyls (PCBs)	Government of Switzerland (2015)

337 n.a.: not applicable

In addition, the new Regulation (EU) 2019/1009 on fertilizer products establishes rules and requirements for the marketing of fertilizers and their use. Some key aspects are the introduction of classification and labeling of fertilizer products. This involves the definition of product function categories (PFCs) and component material categories (CMCs) that cover both the materials used as fertilizers and the raw materials for their production (EPC, 2019; Garske et al., 2020; Nättorp et al., 2019). The regulation also incorporates new CMC concepts such as digestates, animal by-products, struvite, biochar, and sewage sludge and its derived ash, facilitating free trade of CMCs in Europe. Another important change is that it introduces limits for toxic contaminants such as cadmium (Cd), as virgin P fertilizers usually contain significantly higher Cd concentrations than recovered materials (Jupp et al., 2021).

The Netherlands, Switzerland, and Germany have been pioneers in the regulation of fertilizers, driven by specific national standards that focus on P recycling and fertilizer quality criteria. The Netherlands modified its regulations in 2015 to favor the use of struvite as a recycled fertilizer, ensuring regulatory compliance and requiring it to come from sewage sludge treated to eliminate pathogens (De Boer et al. 2018). Likewise, Germany imposes requirements for fertilizers on the market through its ordinance and restricts fertilization with P in soil, encouraging reduced fertilizer usage per unit of crop area along with good agricultural practices (Garske et al., 2020). Switzerland includes pollutants such as persistent organic compounds (POCs) and emerging micropollutants in its quality criteria (Government of Switzerland 2015). These regulations are crucial to mitigating the risks associated with recovered products, along with the need for continued treatment and research into their practice and application.

Another challenge to closing the P cycle is that it requires a circular value chain, in which recovery serves as supply and recycling as demand (Jupp et al., 2021). The phosphate market can currently be characterized as oligopolistic with monopolistic tendencies due to the limited number of provider countries (De Boer et al. 2018). In addition, the low cost is an economic factor to consider when developing a value chain for recovered P products such as struvite (Shaddel et al., 2019). The entry of recovered P into the market falls under the Circular Economy Action Plan, Regulation (EU) 2019/1009 on fertilizers and the WFD (2008/98/EC) in the EU. The WFD establishes end-of-waste (EoW) criteria that must be met by a material for it to cease to be considered waste and become a product made of recovered materials. The EoW criteria depend on the market segment to which the product belongs, and there are specific regulations for recognition as a fertilizer, organic fertilizer, or food supplement. The transition from the category of "waste" to the category of "product" requires compliance with Regulation (EC) No. 1907/2006 (REACH) for the registration, evaluation, authorization, and restriction of chemical substances, as well as the Regulation (EC) No. 1272/2008 (CLP) for the classification, labeling, and packaging of substances and mixtures (Hukari et al., 2016).

In Europe, approval under the REACH legislative framework and fertilizer regulations is necessary for unrestricted marketing. Acceptance of fertilizers with EC certification varies between 5% in Denmark and Sweden and 80-100% in Germany and Spain, and on average they account for approximately 60-70% of the total market volume. However, one of the main challenges of reusing P-containing by-products is that fertilizer

companies cannot accept recovered P products unless they provide some economic benefit to their business (Hukari et al., 2016). For example, the cost of P recovery varies according to different technologies between 2-28 €/kg $P_{recovered}$, with P recovery from the aqueous phase being the most economical (2-10 €/kg $P_{recovered}$), while the price of phosphate rock varies between 0.5-1.2 €/kg P and that of triple superphosphate fertilizer between 1.2-2.2€/kg P. Therefore, the lack of economic incentives and the low market price of P products make recycling unattractive, discouraging the practice of recovering and recycling P in the wastewater treatment sector (Egle et al., 2016).

2.4 Application of recovered phosphorus to soil in agriculture

The main application of recovered P is as a fertilizer in agriculture, although it has other uses such serving as a raw material for the fertilizer industry, construction materials such as cement, biogas production, animal feed, and food (Egle et al., 2015). The Sewage Sludge Directive (86/278/EEC) regulates the use and controlled application of sewage sludge, a rather common practice due to its high nutrient content, although controversial due to micropollutants harmful to health (See Table 3). Although this directive is not specifically focused on P recovery, it addresses the management and use of sludge that can contain P. In addition, it regulates the presence of contaminants and their application, establishing restrictions such as not using them on fruit and vegetable crops or shortly before harvest, and in animal grazing areas (EEC, 1986).

In several European countries, stricter regulations related to the direct application of biosolids on farmland have been implemented due to concerns over the contaminants they may contain. In Germany, Belgium, the Netherlands, and Switzerland, it is prohibited to recycle biosolids as fertilizers on farmland for food safety reasons. In the United States, around 55% of produced sludge is applied to soil for agricultural and land restoration (Shaddel et al., 2019). However, application on land is subject to restrictions on heavy metal content and biosolid application rates, as well as state regulations. In Japan, the direct application of sewage sludge on farmland is not permitted due to environmental and health concerns and the scarcity of available land; therefore, 75% of WWTP sludge is incinerated and the rest goes to landfills (Nättorp et al., 2019).

Local governments and agricultural authorities have implemented regulations that limit P fertilization on arable land (Sarvajayakesavalu et al., 2018). This necessitates a shift in agricultural practices toward adoption of alternative nutrient sources (Barquet et al., 2020). Regulations related to P application in agriculture are currently limited and vary by country or region. For example, Directive 86/278/EEC requires that sewage sludge use take into account the nutrient needs of plants and avoid the deterioration of soil and water quality. Germany promotes good practices to optimize the interaction between P and plants, improving crop yield and quality and preserving soil fertility (Garske et al., 2020). In the United States, Maryland's Water Quality Improvement Act regulates the land application of biosolids with P the same way as fertilizers and manure (Lu et al., 2012). In China the focus has been on sustainable agricultural practices, and the Action Plan for the Prevention and Control of Soil Pollution, including appropriate management of sewage sludge in agriculture, was implemented in 2016 (Sun et al., 2016).

3 Implications and final considerations

Figure 3 shows the level of progress in different geographic regions in terms of the implementation of an institutional framework for P recovery from wastewater. The level of development of this institutional framework was determined based on installation and operation of efficient treatment plants aimed at P recovery, the establishment of strict standards for P concerning water treated discharge (< 1 mg P/L), the implementation of unregulated plans, and regulations related to the recovery, recycling standards, and land application of P (See Table S2). In general terms, Europe is considered the most advanced region in these matters, with countries such as Germany, Netherlands, Switzerland, Austria, and Denmark standing out. These countries prioritize strict circular economy policies and laws. They have a comprehensive approach to water resources management, with broader strategies related to nutrient recovery and sustainable agriculture. These countries emphasize collaboration and communication among government, industry, and researchers to develop sustainable technologies and practices through innovation.

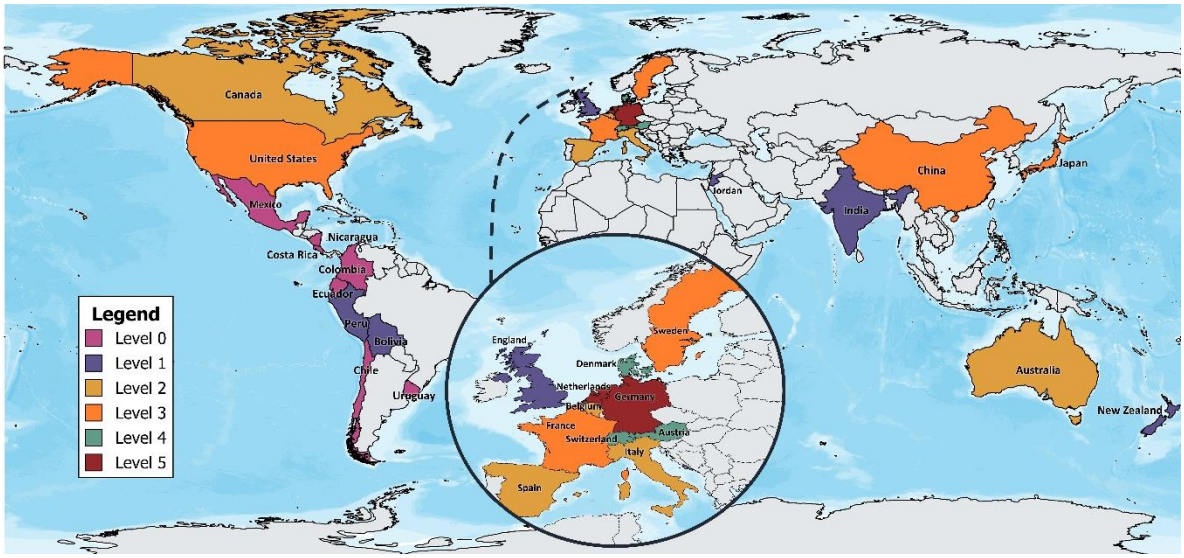

Figure 3. Level of development of an institutional framework for P recovery from wastewater in different geographical regions, with 0 being the lowest level and 5 the most advanced. The existence of 1) P recovery in WWTPs, 2) P discharge standards (< 1 mg P/L), 3) P recovery standards, 4) unregulated plans, and 5) P recycling and land application standards is considered.

In other parts of the world, countries such as the United States, China, and Japan have promoted the closure of the P cycle through the effective operation of existing WWTPs, the installation of efficient technologies, and the implementation of state and national plans for P recovery. These countries stand out for their development of advanced technologies and facilities for nutrient recovery. In terms of environmental policies, measures have been implemented to address water pollution, waste management, and sustainable practices. In Latin America, there has been little progress in wastewater treatment and P recovery. Although there have been improvements in drinking water and sanitation system coverage. This region presents an unfavorable legal and institutional context for innovation, with a weak regulatory framework, unclear goals, and insufficient resource allocation

for the introduction of new mechanisms. Factors such as evaluation difficulties related to system integrity risks and the lack of medium and long-term perspectives resulting from political instability in many countries in the region also play a role (De la Peña et al., 2022).

Differences in the institutional framework between regions are evident. First, the absence in some countries of a common institutional structure that explicitly advocates circular economies, monitors wastewater reuse, and establishes agricultural standards stands out. This absence highlights the lack of a unified objective or governmental priority, especially in terms of environmental protection and water resources regulation (Pulgar-Martinez, 2020). Finally, structural disparities in economic and technological resources, particularly in less developed nations such as those in Latin America, add another layer of complexity. In contrast, countries with advanced technological innovation present greater prospects for the development of nutrient recovery and reuse systems (De la Peña et al., 2022).

Another barrier often overlooked in P recovery is the lack of information on environmental benefits. While the economic costs of P recovery may appear unfavorable initially, it can yield economic benefits through monetary returns from by-products such as energy and nutrients and a reduced need to apply costly chemicals. Furthermore, substantial social benefits with indirect economic value can be achieved. Therefore, in addition to confronting institutional challenges, it is crucial to expand research studies, assess economic feasibility, conduct life-cycle analyses, ensure product quality, and address concerns regarding public acceptance (Chrispim et al., 2019). Consequently, there must be a comprehensive vision for P recovery that encompasses technological aspects, economic incentives, agreements, and political regulations. This approach should also address public acceptance, ensuring both public health and the conservation of natural resources.

4 Conclusions

The institutional framework for P recovery from wastewater is still very heterogeneous and varies by country. Thus, new laws for the promotion and development of P recovery must be implemented in many countries. Europe is the continent where the most progress has been made. Common elements found in existing national regulations concerning P recovery in the EU are the existence of an European-level regulatory framework addressing environmental and waste-regulation issues, the promotion of recovery-oriented strategies by EU regulations and framework guidelines, the establishment of particular goals and deadlines regarding P recovery from wastewater, the formulation of public policies, the existence of incentive mechanisms created by legislation, and an institutional framework for resource recovery mainly focused on local or municipal WWTPs (in accordance with decentralized sanitation management). A challenge for countries outside Europe is to implement a solid, interconnected, and well-structured institutional framework among the involved stakeholders with effective standards and regulations to promote sustainable management of this valuable resource.

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Appendix A. Supplementary data

Supplementary data can be found online at

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