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Transforming the European Union's phosphorus governance through holistic and intersectoral framings

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This review paper presents a critical perspective on the transformation of phosphorus governance in the European Union to support food and environmental security, which are subject to systemic shocks. It presents three major limitations that act as constraints to this process: (1) the predominance of technical studies, which produce isolated meanings that fail to address the socio-political aspect of phosphorus management and cannot be translated into policy foresight; (2) approaches to change dominated by the linear resource efficiency paradigm narrowly confined within sectoral responses to system shocks; and (3) the constrained policy understanding of the circular economy, which hampers system change as phosphorus reuse is seen primarily as part of the biological cycle of the circular economy and does not advance critical perspectives. We argue that the siloed and heavy regulatory load related to phosphorus produces technocratic and incremental policy revisions, singular state-level approaches and reductionist prisms that exclude extraterritoriality. These exacerbate the inability of institutions to translate technical studies into policy foresight and counter the pervasiveness of linearity. Phosphorus requires instead a holistic and intersectoral governance object that is integrated with the multiple transition instruments on the policy-making agenda of the European Union. To achieve phosphorus sustainability and avoid the dependence on shocks for its self-renewal, phosphorus governance needs to overcome the technocratic incrementalism of individual sectors and adapt to alternative discursive framings that transcend the existing compartmentalization of its meanings. This would require disentangling phosphorus as a contested arena of controversial stakeholder priorities and selectively amplifying the discursive framings that can politicize and enhance its ubiquitous importance. While phosphorus has its unique properties, such an approach can be of relevance to other elements.

KEYWORDS

circular economy, European Union (EU), framing, governance, phosphorus, political framing, resilience, transformation

1 Introduction

Phosphorus is essential for sustaining life in all its forms and hence critical to food production as a fertilizer and soil nutrient (Cordell and White, 2014). At the same time, its inefficient management poses a range of environmental risks, such as eutrophication of water bodies (Scholz and Wellmer, 2019). Phosphorus is also strategically important for producing pharmaceuticals, batteries, robotics and microchips (Bobba et al., 2020). Even though it spans roles ranging from food production to traditional security, energy (Dawson and Hilton, 2011) and digital transitions, the perception of fertilizer abundance has limited political attention to phosphorus (Rosemarin and Ekane, 2016) and has reinforced its framing as a polluting substance. This paper aims to provide a new conceptual reading of the field of phosphorus governance that employs holistic and intersectoral framings to move beyond its understanding just as a polluting substance, wherefore it sets out a transformative research agenda that accentuates its broader socio-political importance.

To achieve this, we undertake a critical scoping review, suitable to "address broader topics" (Arksey and O'Malley, 2005, p. 4), map heterogeneous literature (Peters et al., 2021), identify and clarify concepts with transversal dimensions across disciplines (Galego et al., 2022; Gutierrez-Bucheli et al., 2022) and hence suitable to disentangle the complexity of governing phosphorus.

The review focuses on the European Union (EU), which has a plethora of underutilized policy instruments, an established market power in setting influential legal standards, and a central role in international forums that can allow it to steer the global coordination of phosphorus (Schutze, 2004, p. 235; Bradford, 2012; Damro, 2012; Reitzel et al., 2019; Brownlie et al., 2021; Harseim et al., 2021). The review is based on thorough readings of articles obtained via systematic searches (Database: Scopus, years 2000-, combinations of phosphorus and Governance: $N = 8$, phosphorus and Policy: $N = 29$, phosphorus and Innovation: $N = 24$, phosphorus and Management and Governance: $N = 84$), followed by unsystematic searches (Database: Google Scholar, years 2000-present).[1] The articles from the systematic searches were used as the backbone of the unsystematic scoping. The articles were initially organized around themes and were subsequently reorganized around arguments on missing aspects. Lastly, in line with the aims of the article, the results were used to derive and streamline argumentative propositions for future research that could contribute to more holistic approaches and integrate alternative framings to transform phosphorus governance. Since the article attempts to break the established archetypes of siloed analysis, reflecting critically on the published literature, it makes an important bibliographical contribution that bridges critical sustainability and extended inquiry of relevant fields. The following sections outline three major limitations of the current framings of phosphorus governance that stem from its overtly technical nature, the efficiency paradigm, and a limited conceptualization of circularity. Subsequently, it argues for transforming the field through a more holistic approach that integrates alternative framings. In concluding, we propose a new research agenda for phosphorus governance that should investigate the discursive controversies in phosphorus framings.

1 Systematic search refers to the systematic use of the search terms indicated above, while un-systematic search refers to conventional (broader) literature exploration. The year 2000 was identified in the emergence of social science studies with some focus on phosphorus governance.

2 Overview of phosphorus and its dynamics

The prebiotic phosphorus cycle began with marine sediment weathering and oxidation that brought it to land and was followed by processes of biological recycling after life appeared on Earth (Walton et al., 2023). The current phosphorus cycle began with the lifting of tectonic plates and the subsequent weathering of P rock, physically through rain and chemically through fungal acidification (Hoffland et al., 2004), that aided the formation of soils, from where it leaches to rivers and lakes, and returns as sediment on ocean beds (Ruttenberg, 2003). Microorganisms solubilize P, which is absorbed by plants (Rawat et al., 2021) and animals, which in turn, return it to the environment through excretion or alternatively at the end of their life cycle through organic matter decomposition (Guignard et al., 2017). The increase of P concentration in water bodies stimulates the growth of toxic microalgae such as cyanobacteria, that reduce available oxygen, poison aquatic life and have led to over 400 cases of hypoxic dead zones of eutrophication (Oliveira and Machado, 2013). In the long term, the decomposition of the excessive biomass releases further toxins that can be hazardous for birds, cattle, animals and humans, produces greenhouse gases and results in a negative socio-economic impact of 1 billion USD in the EU (Wurtsbaugh et al., 2019). Furthermore, eutrophication hampers the delivery of ecosystem services (Malone and Newton, 2020; Cakmak et al., 2022).

Certain properties of phosphorus make it indispensable for ecological systems, including the role of phospholipids for inter-membrane energy metabolism of the cell (Turner et al., 2018) and the mycorrhiza assisted synergetic phosphorus-carbon exchange during photosynthesis that enhances plant growth and is the cornerstone of agricultural intensification (Fall et al., 2022). Anthropogenic interest in utilizing these effects has driven the extraction and over-application of P that became a precursor to the trade of agricultural crops over large distances, a decreasing productivity of fertilizer inputs, and the introduction of contaminating trace elements (Cordell et al., 2009a; Jiao et al., 2012; Bai et al., 2023). The distribution of phosphorus is also subject to significant losses during transportation and beneficiation, as legacy P in soils, as agricultural runoff and leaching, and in food waste (Rose et al., 2013; Nedelciu et al., 2020).

Phosphorus is also associated with environmental health and human safety issues. Allotropes of phosphorus, such as white phosphorus, may be detrimental to human health (a cause of jaw necrosis) and are known for their pyrophoric property that triggers an incendiary reaction upon exposure to oxygen predicating their use in explosives (Ashley et al., 2011; Geeson and Cummins, 2018). Red phosphorus is used in the production of some illicit drugs such as methamphetamine and in the manufacture of glyphosate—a politically contentious herbicide with potential carcinogenicity (Morton and Edwards, 2005).

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As a commodity, phosphorus has a multidimensional importance as a feedstock for end-use products with growing demand (de Boer et al., 2019). While 90% of P is used for fertilizers, P acid is used in food preservation, fuel cells, and flame retardants, LiFePO4 in batteries, and black phosphorus in transistors, sensors and microchips (Cordell et al., 2009a; de Boer et al., 2019; Bobba et al., 2020). Historically, P was reintroduced to the soil through the application of manure, guano and crop residues, burning of fields and bonemeal. However, applications have increased in volume more than six-fold since the advent of the Green Revolution in the 1950s, when mined P became the prevalent source of fertilizer (Ashley et al., 2011). With socio-economic factors such as diminishing returns on extraction and application, population growth in the global south, increased consumption of meat, and novel industries, there is an expectation of a doubling of P demand by 2050, while climate extremes, rising energy prices and potential ongoing financial, health and geopolitical risks may jeopardize economic security through protracted, sharp fluctuations in P prices (Nedelciu et al., 2020; Brownlie et al., 2023). This is illustrated by Figure 1, which exemplifies the expected stickiness of the price increase of phosphate rock and phosphorus fertilizers during the last decades that were driven by exogenous shocks.

Phosphorus rock was included on the EU's critical raw materials list not because of its geological exhaustibility, but rather for its economic importance and insecure supply (de Boer et al., 2019) as five non-EU countries hold 85% of the remaining deposits, and supply diversification beyond Morrocco, which holds 70%, is limited by China and Russia's export restrictions (Brownlie et al., 2022). On the other hand, tetraphosphorus (P4) was added due to EU's supply vulnerability, which jeopardized the economic security of multiple industries for which its derivatives are a non-substitutable input: firstly, because EU's only P4 producing factory owned by Thermophos was allegedly purchased "with money from a Russian weapons dealer" and subsequently liquidated in 2012 due to competition from Kazakhstan (Joint Research Centre of the European Union, 2012); and secondly, as EU's supply routes are exposed to vulnerabilities stemming from the fact that Vietnam and Kazakhstan as biggest exporters are geographically distant (European Sustainable Phosphorus Platform, 2015; Observatory of Economic Complexity, 2023). By extension, the EU's food security is also vulnerable to geopolitics, as China is the biggest producer of fertilizers and Russia is the biggest producer of Nitrogen-Phosphorus-Potassium (NPK) fertilizers (Randive et al., 2021).

According to life cycle assessment studies, P recovery can redress these environmental externalities, as it brings not only net savings of P rock, sulfur dioxide and dust emissions during the extraction phase, but also reduced aquatic eutrophication, terrestrial acidification and biodiversity loss (Tonini et al., 2019; Lam K. L. et al., 2020). The rectification of these negative environmental impacts could be used to justify regulatory pressures, as "without policy interventions, the linear economy of phosphorus is likely to remain economically most attractive", and to overcome difficulties in translating such transformation imperatives to wider audiences (Sen and Bakshi, 2023, p. 1).

3 Constraints to transforming phosphorus governance

3.1 The limitations of technical studies

Despite the high number of studies with a focus on the impact of phosphorus pollution on water bodies, water quality has not improved due to factors such as the complexity of diffuse pollution streams, inertia in responses to these, as well as associated time lags in implementation (Bieroza et al., 2021). Phosphorus governance remains trapped by isolated dominant logics into a self-reinforcing lock-in that results in the persistence of vulnerabilities, reliance on path-dependent solutions and acceptance of the undesirability of system change (Haider et al., 2018, p. 319). The initial triggers for creating the first regulatory instruments that addressed phosphorus were the eutrophication-related ecological crises in the United States that led to the adoption of the 1972 Clean Water Act (Coale et al., 2002; Johansson et al., 2004). The objectives of the Act are reflected in the EU legal order through the Nitrates Directive (91/676/EEC) and the Water Framework Directive (2000/60/EC). The regulatory aspirations in these legal acts have sparked a significant amount of academic interest to support policymakers in improving the quality of water bodies by reducing and removing pollution (Bechmann and Stålnacke, 2005; Tangsubkul et al., 2005; Schulte et al., 2010; Jordan et al., 2012; Trevisan et al., 2012; Brownlie et al., 2014; Ford et al., 2015; Jedelhauser and Binder, 2015; Gooddy et al., 2017; Macintosh et al., 2018; Bragina et al., 2019; Van Meter et al., 2021). These predominantly technical studies oftentimes investigate individual modeling parameters or spatial planning practices, which focus on place-sensitive physical properties of the analyzed landscapes and water bodies. Since conditions vary, such studies focus predominantly on specific bio-geophysical localities and are less helpful when explaining the role of socio-economic and institutional factors in phosphorus governance more broadly.

Most of the non-technical studies that explore the role of phosphorus as a water pollutant analyze the existing social and political barriers to effective water governance, the interests of and power relations among different stakeholders, as well as the effects of policy instruments in shaping phosphorus governance. Examples include the difficult negotiations between regulatory bodies and agricultural practitioners responsible for the implementation of adopted measures, the influence of powerful corporate lobbies and the weakness of NGOs in protecting water bodies, and the difficulties in cooperating beyond national jurisdictions, while respecting environmental scales (Schulte et al., 2010; Wardropper et al., 2015; Berardo and Lubell, 2019; Friedman and Creed, 2021). Such factors necessitate the use of governance instruments appropriate to the scale of intervention, the utilization of hybrid arrangements and adaptive standards, and the high-level engagement of politicians (McDowell et al., 2016; Tabaichount et al., 2019; Zia et al., 2022).

Two principal lessons can be learned from these social science-focused studies of the water-phosphorus complex. Firstly, "there is a convergence between water quality and phosphorus security research agendas" (Leinweber et al., 2018, p. S3), which could serve as a necessary starting point for analyzing phosphorus

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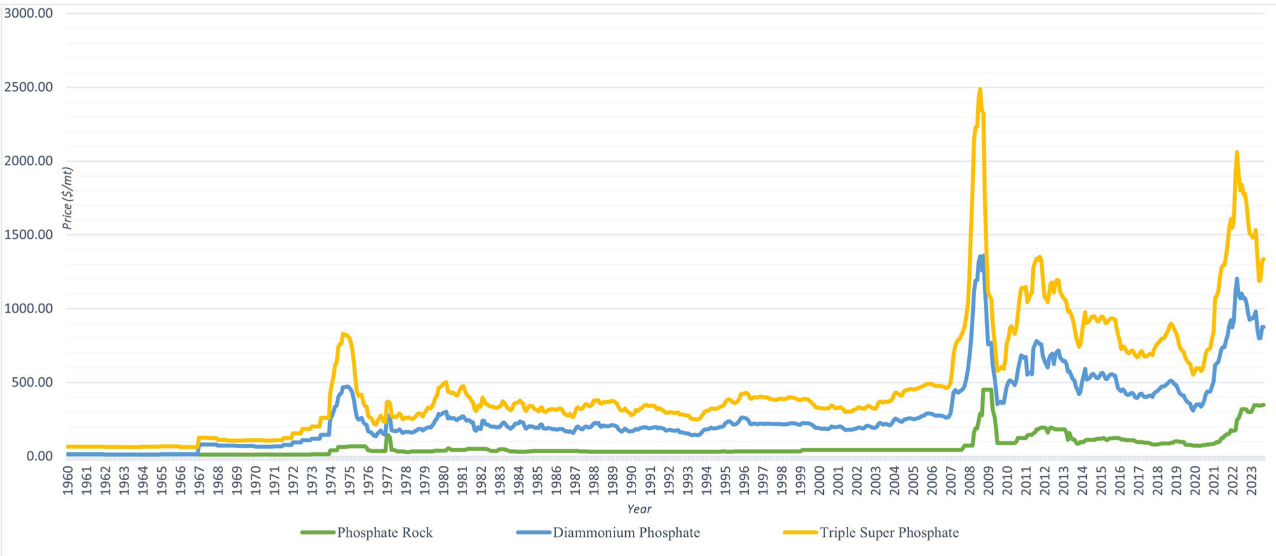

FIGURE 1
Fluctuation in phosphate rock and phosphorus fertilizer prices (World Bank, 2023).

governance. The characteristic asymmetries exhibited in both water and phosphorus governance have triggered substantial interest in phosphorus stocks and flows, and their effects on water quality. However, such prisms may fail to recognize that inefficient management is multidimensional. Secondly, context-sensitive technical studies are unable to address the socio-political aspects of phosphorus management more broadly. By extension, the same logic can be applied to purely technical studies related to plant roots and mycorrhizae' (Madrid-Delgado et al., 2021) or inoculated microbial communities' (Chen et al., 2021) ability to absorb phosphorus, the chemical properties of phosphorus polymers (Zhang et al., 2021), assessment of the viability of industrial recovery installations (Kataki et al., 2016), medical applications (Monge et al., 2011), or the electrical conductivity properties of phosphorus (Zhang et al., 2010; Wilkins et al., 2013). It is unlikely that these studies can initiate transformative countermeasures from the isolated technical meanings they themselves produce.

3.2 The persistent vulnerability to system shocks

Besides being an environmental pollutant, phosphorus has gathered attention predominantly because of its characteristic as a scarce non-renewable resource prone to system-wide shocks. For example, the 2007–8 financial crisis that triggered Chinese export tariffs (Cordell et al., 2009a; Chowdhury et al., 2017) and the COVID-19 associated supply-chain disruptions, exacerbated by the shocks on food and energy security resulting from Russia's invasion of Ukraine (Brownlie et al., 2023), drastically increased commodity prices of P in 2021–22. These developments affected farmer livelihoods, crop production and drove global food crises. Concomitant with the associated price shocks, the concept of peak phosphorus provided a framing of phosphorus as a scarce and finite resource that compelled the pursuit of resilient governance systems (McGill, 2012; Scholz et al., 2013). However, shifting the debate from alarmist definitions of the phosphorus challenge to problem-solving instruments has been irresolute (Ulrich, 2013) and has been possible only through the exposure of the phosphorus system to multiple shocks that alerted policymakers and the academic community.

The criticality of food production for the stability of human societies can be seen as the reason why substantial scholarly attention has focused on and defended a food security prism for phosphorus governance. Many studies investigate phosphorus vulnerability as a result of multidimensional scarcities, among which are existing international institutional arrangements for phosphorus supply (Cordell and Neset, 2014; Cordell and White, 2014; Nanda et al., 2019, 2020), dietary change for phosphorus demand reduction and improved alignment with planetary boundaries (Ashley et al., 2011; Cordell et al., 2011, 2022; Metson et al., 2012; Vitousek and Liu, 2019). Yet, these contributions have been limited to the sectors of food and the environment. For example, in the aftermath of the 2009 financial crisis, phosphorus recovery for usage in agriculture was seen as competing for investment with renewables (Cordell et al., 2011), while the realization of the EU's dependency on Russian hydrocarbons in the aftermath of the Ukraine crisis allowed the two perspectives of global food security and investments in synthetic fuels to be brought together in the EU's Ensuring availability and affordability of fertilizers communication [COM(2022)590, 2022]. The slow divestment away from such compartmentalized logics has been a main reason for the evolutionary stagnation of policy-relevant knowledge regarding phosphorus. Consequently, phosphorus remains continuously clenched in strictly sectoral analyses by scientists with predominantly technical backgrounds, whose reasoning is difficult to translate to policymakers and subsequently fails to advance new understandings of phosphorus governance.

In the institutional realm, the phosphorus policy agenda has been framed through the Roadmap to a Resource Efficient Europe [COM(2011)571, 2011], which defines transformations through a path-dependent rationale that focuses on economic competitiveness and policies fostering an enabling business environment. The subsequent 2013 Consultative Communication on the Sustainable Use of Phosphorus outlines priorities such as security of supply, which allowed phosphorus to be added to the Critical Raw Materials List and shift efforts toward recycling (Smol et al., 2020). This, together with diversifying supply and opening domestic mines in line with the Critical Raw Materials Act [COM(2023)160, 2023], complements resource efficiency. The problem is firstly that the exploration of primary resources and the potential rebound effects of recycling are continuously maintaining a linear growth paradigm (see Section 1.3.) and secondly, that resource efficiency has remained a reductionist version of circularity (Section 2.2), which limits the debate about phosphorus governance and the emergence of alternative framings of phosphorus.

The lack of a coherent articulation of concepts such as cycling, circularity, circularization, recovery and recycling in the academic community, as well as the dominance of certain policy rationales that perpetuate linearity narrow the scientific debate as to how the social sciences can assist policymaking. For example, critiques of the existing policy rationale of input-output resource efficiency focus on the fact that such a formulation does not contribute to eco-efficiency and occupational health (Scholz and Wellmer, 2015). They neglect wider debates of conflicting interests (see Section 2.3.) (Nesme and Withers, 2016, p. 260), policy-induced rebound effects (Vivanco et al., 2018) and stifle any discussions about more ambitious and holistic phosphorus transitions (Ulrich, 2016; Shen et al., 2019).

What is more, the ubiquitous potential of phosphorus to drive system transitions has not been identified by the institutions of the EU. Phosphorus can serve as example for the framing of other non-renewable resources through the usage of stewardship of instruments of relevance to natural resources and improving their ability to cushion exogenous shocks (Jarvie et al., 2015; Withers et al., 2015). Further possibilities include capitalizing on system directionality possibilities through intelligible concepts such as the resource hierarchy, which prioritizes reducing the demand for resources, their carbon intensity and improving their reuse before proceeding to recycling and recovery of value based on resource upcycling (Barquet et al., 2020; Nilsen, 2020).

3.3 The constraints of the circularity hype

The linear phosphorus efficiency paradigm set out by the Roadmap [COM(2011)571, 2011] can be traced further into the circular economy, a concept that has been embraced by a long list of scholars as a potential basis for future policy framings (Scholz, 2017; Jedelhauser et al., 2018; van Leeuwen et al., 2018; Withers et al., 2018; Smol, 2019; Barquet et al., 2020; Geissler et al., 2020; Golroudbary et al., 2020; Rosemarin et al., 2020; Smol et al., 2020; Valve et al., 2020; El Wali et al., 2021; Peterson et al., 2021; Stamm et al., 2022, p. 618–619). The circular economy concept consists of two cycles: a biological cycle that returns organic material to the biosphere and a technical cycle that creates value through capturing and recirculating materials in the economy (Ellen Macarthur Foundation, 2013). It is praised as a restorative "economic model based on the renewability of all resources" (Fidélis et al., 2021, p. 2; Geisendorf and Pietrulla, 2018). The circular economy constitutes an "operational concept for orchestrating post-linear regenerative" economy (de Jesus et al., 2019, p. 1501). It also constitutes a boundary object with a toolset of practices that can guide the appearance of niches and regime change (Franco-Torres et al., 2020). However, its application to phosphorus is still in its infancy and suffers from several limitations.

Largely due to economic and technological complications arising from the recovery of phosphorus and the lack of economic instruments to support its reuse and value recovery, circular phosphorus economy framings have focused on removing phosphorus from wastewater, while the reutilization of phosphorus has been largely ignored (Jupp et al., 2021, p. 98). The current policy prioritization of recycling and incineration in the circular economy remains controversial, as it comes to the detriment of elements higher in the waste hierarchy, such as repurposing and remanufacture, which limits the possibility of an institution-driven innovation-focused framing to align value chains, firms and individuals that may be interested in emission abatement technologies (Hansen and Schmitt, 2021). The circular economy also promotes a limited understanding of phosphorus as an "organic nutrient… captured as valuable byproduct for subsequent use" (Ellen Macarthur Foundation, 2021, p. 38) because "sectors dealing with the biological cycle" are gaining less scientific attention. In addition, fertilizers from virgin materials do not factor in supply chain externalities (Suchek et al., 2021, p. 3696–3697). The societal understanding of phosphorus as a mere polluting nutrient is further entrenched by the EU imperative to defend an innovation-based solutionism to societal problems (Pfotenhauer et al., 2019). For example, Horizon Europe Missions have been conceptualized as a possibility to generate bottom-up foresight and citizen-led innovation (Mazzucato, 2019; Weber et al., 2019; Rosa et al., 2021, p. 8–12). However, the prevalent logic of current phosphorus-related Horizon Europe calls with repercussions for the wider Soil and Oceans Missions, as well as the EU Green Deal, limit such aspirations to the implementation of top-down policies to improve fertilizer use efficiency, constraining the associated adverse effects of phosphorus pollution on land and water bodies (see Section 2.1) (Horizon Europe, 2023). In this sense, no attention is paid to how recovered phosphorus can be used in the technological cycle of the circular economy. These limited aspirations for reuse of recovered phosphorus to agriculture due to current technological or purity constraints may point to a lack of political will for system change in EU institutions.

As EU institutions still predominantly understand phosphorus circularity as the cycling of phosphorus within farming systems (Oster et al., 2018), phosphorus policy debates have been largely locked into healthy soils and efficient agriculture within the EU Green Deal (see Section 2.1). Because of this compartmentalized approach, recovery targets for phosphorus have appeared much more slowly on the EU's policy agenda. Recycling as a form of resource recovery can generate resistance from many stakeholders in the linear economy, including farmers, workers in mines, fertilizer and wastewater plants. Additional resistance can come from academics and businesses that emphasize recycling's carbon intensity to deter aspirations for limiting reliance on imports, which may damage their business profitability (Teah and Onuki, 2017; El Wali et al., 2019; Golroudbary et al., 2019; Jupp et al., 2021). These actors regard the recovery of energy and raw materials (such as struvite, biogas, bioplastics, and cellulose) as an expensive operation and subsequently prioritize virgin materials under a deficit scenario (van Leeuwen et al., 2018; Golroudbary et al., 2020). On the other hand, although some academics claim circularity is inevitable for transitioning away from linearity (Scholz, 2017; Steiner and Geissler, 2018), others note that recycling alone is not sustainable in the long run and can substitute only 15–17% of phosphate rock imports into the EU (Golroudbary et al., 2019). Studies that analyze business-as-usual scenarios (see Figure 2) have shifted the focus toward demand and supply framings interpreted as agricultural efficiency and recycling rates (Cordell et al., 2009b, 2011; Cordell and White, 2013). However, neither circularity as fertilizer efficiency, nor phosphorus recycling are challenging the deeply underlying problems such as decoupling of pricing from resource scarcity (Chowdhury et al., 2017) or the appearance of systemic shocks. What is more, they are shifting the attention away from systemic supply chain analyses of phosphorus embeddedness in trade flows, as well as government interventions that can correct markets' limitations to circularity.

Since the circular economy is one of the main framings of phosphorus-related research, some more general critiques can also be applied to phosphorus. To begin with, the circular economy's technocratic focus on resource efficiency limits the EU's policy aspirations for waste-target updating (Calisto Friant et al., 2021, p. 346–347). This shortcoming constrains the design of "radically innovative solutions" (Borrello et al., 2020, p. 9) and can be justified with pressures stemming from the economic recession and growth imperatives (Fitch-Roy et al., 2020).

Besides its rudimentary adoption, the circular economy has been criticized as a heterogeneous and incoherent amalgam of definitions: a "fragmented collection of ideas (...) and semi-scientific concepts"; a product of intra-institutional policy layering and patching that does little beyond emphasizing the importance of high-quality material cycles and a sharing economy (Kirchherr et al., 2017; Korhonen et al., 2018, p. 39; Fitch-Roy et al., 2020). What is more, it is usually portrayed without elaborating more critical views on social sustainability, labor exploitation, or its lack of reconfiguration capacity (Jedelhauser and Binder, 2018; Nedelciu et al., 2019; El Wali et al., 2021). The EU's failure to highlight these aspects enables corporate reputational greenwashing, such as service economy of extended repairs and lease schemes being used to maintain ownership of products and the resources embedded therein (Linder and Williander, 2017; Stål and Corvellec, 2018; Hofmann, 2019; Corvellec et al., 2022). Consequently, much of the scholarly attention has been continuously focused on recycling (Allwood et al., 2011; Ghisellini et al., 2016; Kirchherr et al., 2017) and misses the opportunity to challenge linear overconsumption as a rebound effect native to liberal capitalism (Gregson et al., 2015; Hobson and Lynch, 2016; Isenhour and Reno, 2019; Fitch-Roy et al., 2020; Niskanen et al., 2020; Corvellec et al., 2022).

In sum, although the circular economy is widely acclaimed by phosphorus scholars as a solution to unsustainability, in its current form it protracts incremental policy change at the margins (e.g., pollution remediation or recycling rates) rather than transform phosphorus governance. This results in additional bidirectional stickiness between technological change that implements policy rationales, but also feeds back into incremental revisions of governance. In a wider sense, the circular economy's bounding understanding of phosphorus can also be seen as a lack of political will at the EU level to change the system. More critical rethinking of circularity in terms of vested interests, agenda capture and alternatives beyond recycling, such as regeneration in a circular bioeconomy, repurposing waste streams for reuse in technical cycles and modularity for parsimonious technological scaling are needed.

4 Toward a reconceptualization of phosphorus governance

4.1 Arguing for a more holistic and intersectoral governance approach

Phosphorus, together with carbon, oxygen, nitrogen, and sulfur is among the main elements constituting all life on Earth. In contrast to nitrogen, carbon and sulfur, phosphorus does not have a stable atmospheric phase or a gaseous form that can assist its synthesis and distribution (Dias et al., 2020; Fu and Zhang, 2020). For example, given sufficient energy, the nitrogen synthesized from air and hydrogen synthesized from water can be fixated into ammonia, which is easier to transport (Ghavam et al., 2021). Rather, phosphorus exists as geographically-discrete, concentrated mineral deposits, which makes it more geopolitically sensitive than other elements. Furthermore, carbon, nitrogen and sulfur are already subject to more specific governance, making the consideration of phosphorus governance of critical importance. However, since the governance of all elements requires improvements, lessons from the analysis presented here for phosphorus can be drawn more generally for other minerals and non-renewable resources.

Currently, phosphorus is predominantly governed in the EU as an inefficiently applied and polluting fertilizer (see Section 1.2.) under a plethora of policy and regulatory instruments governing aspects of environmental protection, resource security, agriculture and climate change (Table 1).

The most sizeable and recognizable aspect of phosphorus governance is within the domain of environmental protection, which incorporates waste, pollution and chemicals safety. Since waste and pollution have been part of EU Environmental Policy since 1972 (Fitch-Roy et al., 2020) phosphorus is governed by a complex set of indirect laws that produce a regulatory lock-in (Arata et al., 2022). Their focus on recovery technology and market placement of recycled materials is faced with a restrictive understanding of the end-of-waste status of secondary materials in the Waste Framework Directive, as well as a chemicals registration mode through REACH directive that is oriented toward safety (Hukari et al., 2016; Ohtake and Tsuneda, 2018; Ross and Omelon, 2018). There is also an insufficient use of best technologies and practices (Rosemarin et al., 2020), which are seemingly addressed by the innovation scaling focus of the EU Missions. The resource security prism instigated by the critical raw materials list is meant

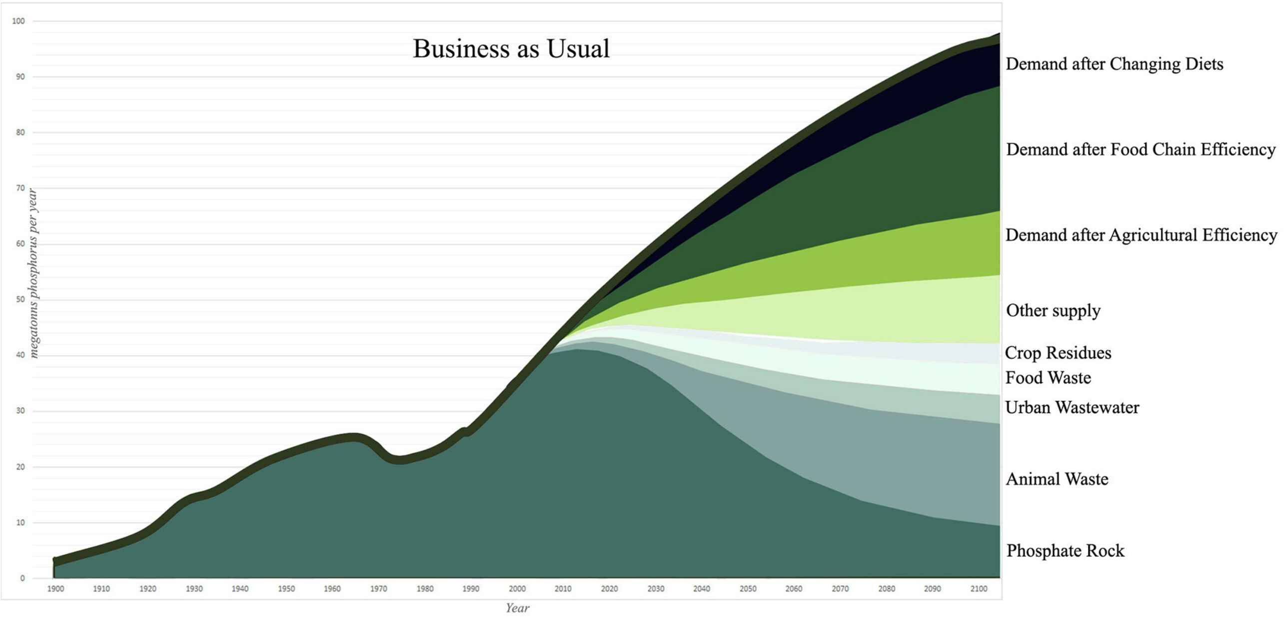

FIGURE 2
Demand and supply framing of P governance, adapted and reproduced from Cordell et al. (2009b). With permission from the copyright holders, IWA Publishing.

to deal with the repercussions of commodity market volatility for supply chains in multiple sectors [COM(2011)25, 2011] and was recently complemented by a proposal for a legislative act [COM(2023)160, 2023]. The most recognizable and prevalent policy is, however, in the domain of agriculture, where the Farm to Fork Strategy, the agricultural pillar of the EU Green Deal, outlines a top-down target of 50% nutrient loss reduction conducive to 20% fertilizer use reduction, as well as 50% chemical pesticide reduction [COM(2020)381, 2020]. However, the common agricultural policy is not clearly aligned with these targets, as they remain largely voluntary (Heyl et al., 2023). The prevalent importance of the climate change domain is included through the interim Fit for 55 Climate Strategy for 2030, which introduces carbon reporting for fertilizers that will turn into a full-fledged carbon border adjustment mechanism from 2025 and complemented with ecosystem restoration as a carbon sink [COM(2022)304, 2022; Council of EU, 2023].

Based on the strategies and various acts outlined in Table 1, we found that pollution and waste are predominantly governed by directives, which allow member states discretion in choosing the modalities of implementation, while market authorization instruments predominantly consist of regulations, which are uniform across member states. Even though the current regulatory regime is subject to uniform risk control, the state-level divergences resulting from different approaches to transposing directives are further exacerbated by the EU applying different risk approaches across sectors. For example, although phosphorus is subject to limitations in Detergent Regulation (EU 259/2012, 2012), it is authorized as a plant protection product through an implementing regulation (EU 2015/1166, 2015). Furthermore, there are intra-sectoral divergences as the top-down targets of the EU Farm to Fork are not well integrated with the current Common Agricultural Policy (Heyl et al., 2023), but only with the bottom-up EU Missions. The current resource security domain is under continuous development and the climate change domain is postponed until the first solidifies.

This thematically siloed and heavy regulatory load limits work toward improvements to incremental revisions of legislation and is coupled with a state-driven focus on single approaches to dealing with phosphorus recovery. The three major examples include:

- sewage sludge treatment that restricts technical recycling, but can produce biogas, as for example in Sweden (Ohtake and Tsuneda, 2018, p. 3–27);
- energy-intensive ash-incineration, which is prioritized in Germany and Austria. It neutralizes health hazards such as pathogens, synthetic chemicals and plastics otherwise contained in direct sludge application, but leads to controversies with regards to energy decarbonization and climate neutrality (Santos et al., 2021); and
- transition to a circular bioeconomy, which requires major shifts in societal organization and resource sourcing and leads to controversies between acceleration and reduction of nutrient application (Holland Circular Hotspot, 2019).

These possibly conflicting state-level approaches make the phosphorus agenda a contested policy arena and may allow further divergence in approaches undertaken by separate institutions. Overall, the combination of siloes, incrementalism and fixation on singular approaches produces a fragmented, compartmentalized and wicked policy arena, where stakeholders promote narrow framings stemming predominantly from the path-dependent understanding of phosphorus as a pollutant.

TABLE 1 Phosphorus governance instruments in the EU.

Policy domain	Instrument	Objective	References
Environmental protection	Chemicals strategy for sustainability	Safety and sustainability by design as basis for innovation	COM(2020)667, 2020
	Reach regulation EC/1907/2006 Detergent regulation 259/2012/EU	Protection of human health and the environment from harmful chemicals	EC 1907/2006, 2006; EU 259/2012, 2012
	Nitrates directive 91/676/EEC, integrated pollution prevention and control directive 96/61/EC, water framework directive 20/60/EC, groundwater directive 2006/118/EC, marine strategy framework directive 2008/56/EC, industrial emissions directive 2010/75/EU, national emissions ceiling directive 2015/2284/EU	Monitoring and control of water pollution to achieve good environmental status	Barquet et al., 2020; Classen et al., 2022
	Sewage sludge directive 86/278/EEC, urban wastewater treatment directive 91/271/EEC, animal by-products regulation 1774/2002, waste framework directive 2008/1998, fertilizer products regulation 2019/1009	Waste safety and waste as potential resource for recovery	Barquet et al., 2020; Classen et al., 2022
	Mission soil deal for Europe, mission restore our ocean and waters	Scaling of innovative local practices to reduce phosphorus pollution	Horizon Europe, 2023
Resource security	EU critical raw materials list communication, raw materials act	Reduce supply risks of strategic resources, increase raw materials circularity	COM(2011)25, 2011; Jupp et al., 2021; COM(2022)590, 2022; COM(2023)160, 2023
	EU fertilizer communication	Secure supply and affordability of fertilizers	COM(2022)590, 2022
Agriculture	Green deal—farm to fork strategy	50% nutrient loss reduction conducive to 20% fertilizer use reduction 50% reduction of chemical pesticides	COM(2020)381, 2020
	Common agricultural policy	Control diffuse pollution, reduce dependency on chemicals	Heyl et al., 2023
	Implementing regulation (EU) 2015/1166	Defines ferric phosphate as low-risk plant protection product	EU 2015/1166, 2015
Climate change	Fit for 55 climate strategy	Carbon reporting and carbon border mechanism for imported fertilizers	Council of EU, 2023
	Proposal for a nature restauration regulation	Restore ecosystems to remove and store carbon	COM(2022)304, 2022

The scientific debate about the paucity of phosphorus governance in the EU is premised on a critique of the incrementally reductionist approach focusing on efficiency improvements that cannot address extra-jurisdictional externalities or socio-political priorities that phosphorus can contribute to. The negative impacts of increased phosphorus application and the hitherto deployed responses were fomented by two distinct processes: firstly, agricultural intensification practices and the associated decoupling of animal husbandry from cropping systems, which were adopted in Western Europe in the aftermath of the Second World War. Purchased primary stocks of plant nutrients thus became the standard practice to increase yields rather than using recycled nutrients within the farm system (Ashley et al., 2011; Cordell and Neset, 2014). A rethink of system efficiency practices into ones that do not increase the nutrient surplus and leaching was necessitated by the 2004/2007 Eastern Enlargement of the EU with further 12 Member States, as it would increase system stress (Larsson and Granstedt, 2010). Secondly, the creation of a dedicated Leibniz Phosphorus Science Campus in Rostock, which focuses on countering phosphorus scarcity by advancing recycling strategies and has produced substantial critiques of the regulatory practice (Roth, 2013). Their legal analyses of phosphorus governance shine a light on the prevailing incrementalism of "small-scale regulatory improvements" (Ekardt et al., 2011, p. 89). Their studies highlight the shortcomings of the EU's technocratic focus on specific products, topics and industries (Ekardt et al., 2015), as well as the lack of complementary sufficiency and consumption reduction instruments that can reinforce phosphorus demand reduction and restructuring of specific sectors (Stubenrauch et al., 2018). Instead, the Leibniz researchers defend the case for economic instruments, such as tax reforms or tradeable phosphorus certificates (reminiscent of emission trading and the UN REDD+), as better suited to address the fact that phosphorus is "virtually" embedded and traded through a range of commodities, which are difficult to regulate separately (Ekardt et al., 2011, 2015; Garske et al., 2018; Stubenrauch et al., 2018; Garske and Ekardt, 2021). Another important argument for moving beyond top-down regulatory targets is premised on the inherent spillover effects from goal setting related to the energy transition or the phasing out of fossil fuels, which can contribute to associated problems of biodiversity loss. Command-and-control law, as currently practiced for phosphorus governance in the EU, therefore, has an inadequate steering effect and is unsuitable for governing complex problems (Garske and Ekardt, 2021).

Instead, the reorganization of resource usage requires strong and coherent public steering that can drive intersectoral restructuring (Valve et al., 2020). Options to achieve that have been put forward in the form of proposals for joint nitrogen and phosphorus management (Kanter and Brownlie, 2019) and overarching legal instruments such as soil law (Stubenrauch et al., 2021), which have already influenced the EU agenda. In line with the 2030 "Fit for 55" climate transition targets, the EU aims to address carbon leakage from production offshoring caused by multinational corporations in avoidance of the EU emission trading system. From 2025, the EU will introduce the Carbon Border Adjustment Mechanism, an import tax that extends to fertilizers not produced in line with climate neutrality goals (Pirlot, 2022). Not least, in line with the proposal for a nature restoration law that will contribute to biodiversity and carbon farming, phosphorus-based fertilizers ought to be reduced by at least 20% through 50% reduction of their losses in the environment [COM(2020)381, 2020; COM(2022)304, 2022]. Through the chemical properties of pesticides, which may have repercussions for environmental, animal and human health, phosphorus can also constitute a sanitary or phytosanitary barrier in EU trade agreements with third countries or regions (World Trade Organization (WTO), 1998). The incommensurable complexity of phosphorus-related instruments and their associated effects is thus insufficiently interwoven into the hierarchy of EU Law as a unitary, integrated and holistic governance object. Furthermore, an in-depth analysis of the interests and the infrastructure that have motivated these emergent instruments is lacking.

Lastly, the dominant understanding of phosphorus governance is strictly bound to the top-down efficiency rationale formulated by the EU as 50% loss reduction conducive to 20% fertilizer use reduction [COM(2020)381, 2020]. Such a regulatory target at the helm limits societal efforts to marginal and incremental changes as it neglects alternative priorities such as food production reshoring to reduce P footprint from imports (Fuchs et al., 2020). Neither can it create a sense of "common purpose" (Ross and Omelon, 2018, p. 656) or address phosphorus embeddedness in traded commodity crops, which outsources environmental degradation (Barbieri et al., 2021; Lun et al., 2021). More importantly, however, it fails to recognize the important roles of phosphorus in defense and military applications, electric vehicle battery manufacturing (Rosemarin and Ekane, 2016, p. 265), pharmaceuticals, robotics, drones, internet and communication technologies (Bobba et al., 2020), which are a necessary element of a holistic, integrated and overarching phosphorus governance regime. One example of these limitations refers to the bottom-up EU Soil and Oceans Mission, which provides a directionality opportunity by advancing both scientific frontiers and technological readiness. However, the Mission's prevailing view of phosphorus is dictated by the top-down fertilizer efficiency rationale (see Section 1.3) and misses opportunities to uphold an integrative, intersectoral and cross-level defragmentation of phosphorus governance through emergent opportunities such as the evolving Climate Change Mission of the EU (Clima, 2023). Thus, besides supporting linearity through its rebound effects (see Section 1.2.), the efficiency rationale is unable to address extraterritorial effects and intersectorality, and incorporate emergent opportunities for phosphorus system directionality.

4.2 The promise of alternative framings

To advance more holistic, integrated and overarching governance, EU institutions should formulate a governance object, whose framing is sufficiently engaging, adaptive and conformable with sustainability principles. From the arguments derived above (1.1., 1.3., and 2.1.), we find that currently phosphorus institutions cannot translate the plethora of technical studies into policy foresight, nor counter the linearity that permeates into circularity and protracts a resilience paradigm. Thus, while phosphorus governance remains preoccupied with technocratic incrementalism that produces narrow understandings, it will not be able to lead a transformative agenda. It can even exacerbate vulnerability to systemic shocks.

As a first premise of resource sustainability, technocratic phosphorus institutions, which are characterized by resilience to uncertainty achieved via managing environmental and health risks in neglect of socio-political factors, should move from a focus on stability through marginal adjustments to achieving long-term purpose and openness to a range of inputs (Handmer and Dovers, 1996). Secondly, such institutions should be able to elevate socio-technical framings of phosphorus that contribute to the substitution of primary resource usage as "the intrinsic objectives of the governance system for P" (Rosemarin and Ekane, 2016, p. 265). Transforming such micro-level technical advancements "to deep leverages of change in wider system structures" (Sievers-Glotzbach and Tschersich, 2019, p. 2) would necessitate a careful analysis of path-dependent structures and vested interests (Nanda and Kansal, 2021). Thirdly, such an anchoring of framings that provide sustainability leverage through the prioritization of macro-system objectives rather than parameter-oriented goals (Meadows, 1999; Leventon et al., 2021, p. 4) should be able to address the disciplinary and legal fragmentation that reinforces the narrow sectoral objectives, windows and logics of policy design (Ekstrom and Young, 2009; Bowmer, 2014; Osherenko, 2014; Hukari et al., 2016; Blankesteijn, 2019; Barquet et al., 2020; Valve et al., 2020; Häggmark and Elofsson, 2021). The wickedness of phosphorus requires an enhanced understanding of the individual elements of the system (Shiroyama et al., 2012) and necessitates intersectoral knowledge integration of loosely coupled, partially overlapping and conflicting framings (Raustiala and Victor, 2004; Keohane and Victor, 2011). Bearing in mind that EU documents function as cross-scale and cross-sector "gateways" that mobilize bottom-up participation in policy formulation, generating dedicated phosphorus instruments can provide directionality to stakeholder efforts (Ahlström and Cornell, 2018, p. 2).

There are four main factors that need to be considered to achieve such a vision of sustainability: firstly, sector-confined approaches to governing phosphorus are unable to address adjacent issues. This is exemplified by claims that a food security focus of phosphorus governance cannot address nutrient loading in soils and water (Belinskij et al., 2019), and that the narrowness of objectives crowds out "locally appropriate solutions with one-size-fits-all" approaches (Barquet et al., 2020, p. 8). Secondly, since ~10 years are necessary for scientists to move from one focus on phosphorus to another one and since phosphorus governance has been adjusting to recovery since 2015, such instruments ought to overcome short-sightedness and slow adaptation to emergent challenges (Ulrich, 2013; Blankesteijn, 2019). Thirdly, what is currently lacking is an accommodation of evolving socio-ecological knowledge through interpretation of the chemical properties and technological uses of phosphorus in line with the "complex, high-level stakeholder... priorities" that characterize the policy-making agenda (Lyon et al., 2022, p. 232; Zia et al., 2022). Lastly, although food security was politicized in the aftermath of the Ukraine invasion (Brownlie et al., 2023), phosphorus governance should not be reliant on external shocks to redefine its meanings, but rather actively scan the horizon for framings of strategic importance.

Solving the governance compartmentalization goes through the elaboration of existing understandings of phosphorus to stabilize its multiple sectoral meanings, but also selectively reinforcing the positive feedback from emergent framings (Graziano et al., 2021). An important consideration in this regard is the incorporation of framings generated by actors that reside "outside the institutionalized system" of participatory channels that contribute to the policy cycle in the EU (Jedelhauser and Binder, 2018, p. 15), as well as going beyond the praise of technological solutions, cutting across stakeholder groups and improving their awareness of emergent developments (Nanda et al., 2020). More holistic approaches have the potential to overcome socio-ecological wickedness through the non-linear co-production of knowledge (Jacobs et al., 2017) to develop cross-border, cross-sector (Macintosh et al., 2018, p. 853–857) and cross-scalar transition pathways (Peterson et al., 2021). Overcoming the sectoral siloes of knowledge and lock-ins to specific infrastructure solutions or governance legacies (Pearce, 2015; Cordell et al., 2016; Iwaniec et al., 2016), such as the efficiency rationale, are some of the necessary preconditions for the identification of such holistic framings. Finally, enhancing such alternative discourses requires a careful examination of the context from which they emerge, how they fit with institutional priorities, and their ability to mobilize stakeholder networks and extra-institutional cooperation alike.

4.3 Integrating alternative framings to transform phosphorus governance

Possibly due to the societal preoccupation with carbon governance, current socio-political research is lacking an elaborated analysis of the discursive framings of phosphorus that can bridge stakeholder controversies and drive bottom-up momentum for inclusion of phosphorus on the political agenda through appropriate issue framings that can define the policy options for transforming its governance (Vaz et al., 2022).

Naturally, amplifying such framings (Lam D. P. M. et al., 2020) and the associated socio-economic restructuring may result in functional exclusion of certain groups during transitions to a transformed socio-technical reality (Geissler et al., 2018; Jedelhauser and Binder, 2018). In consideration of existing modes of operation for fairness in transitions, phosphorus governance should provide an acceptable operating space in a manner akin to common but differentiated responsibilities that drive action toward carbon neutrality (Li et al., 2019, p. 227). There is, however, powerful resistance to the emergence and stabilization of alternative framings, involving governments captured by industrial interests, political parties focused on resource extraction, farmers prioritizing productivity, large supermarket chains limiting food networks, fertilizer companies with vested interests to increase sales, or governments unwilling to update infrastructure without dedicated funding (Kanter and Brownlie, 2019, p. 6, Iles, 2021; Goswami and Rouff, 2022, p. 2). Many of these parties may be the losers from transitions to more sustainable and non-linear phosphorus usage and be unwilling to engage in—or seek to block—transformations.

The vested interests of existing stakeholders may explain why there are conflicting priorities across political levels. For example, there is a waste incineration focus in central Europe that goes against EU climate goals and the EU waste hierarchy (Drangert et al., 2018; Ohtake and Tsuneda, 2018; Amann et al., 2022, p. 8). And some local governments prefer to focus on anaerobic digestion instead of reusing phosphorus, even though they are not mutually exclusive (Papangelou et al., 2020; Classen et al., 2022). On the other hand, a critical investigation of phosphorus-related controversies from the prism of private interests can reveal why industrial infrastructure and technological innovations are prioritized differently by various actor groups (Fuenfschilling and Truffer, 2016; Jedelhauser and Binder, 2018; Ekman Burgman and Wallsten, 2021). Propositions for framings that emphasize technological and innovation-based solutionism should therefore be carefully examined before integration with the phosphorus agenda.

Overall, phosphorus governance unfolds in a disentangled arena of controversies, where actors promote their mandates within sectoral confinements, resulting in multiple goals that are scattered across sub- and sectoral domains, mismatched efforts at innovating and ultimately having "no single goal on the policy agenda" (Shiroyama et al., 2012, Hoppe et al., 2016; Kuokkanen et al., 2016). The lack of directionality and coordination may therefore be understood as a result of conflict avoidance between stakeholders, which can otherwise bear productive tensions (Nedelciu et al., 2019, p. 748). Examining actor motives, values, power and influence (Withers et al., 2020), how the divided science system resonates with goal setting (Blankesteijn, 2019), and integrating authorities, industry and non-governmental networks to bring science, practice and policy together (Stamm et al., 2022, p. 618–619) may ensure both the legitimacy of proposed interventions and the circumvention of informal governance practices.

The coalescence of these social, legal and scientific siloes can address the "small-scale regulatory improvements" (Ekardt et al., 2011, p. 89), and the restrictive, indirect and heavy regulatory load (Hukari et al., 2016; Ohtake and Tsuneda, 2018, p. 56, Ross and Omelon, 2018; Arata et al., 2022). The stringency of the legislative acts governing phosphorus use efficiency, risk management and reuse in products can also lead to displacement of environmental externalities as imports of phosphorus may also be "virtually" embedded in agricultural commodities and other products (Nesme and Withers, 2016; Fuchs et al., 2020). The current efficiency-focused agenda is unable to conceptualize phosphorus management as a political issue (Leinweber et al., 2018), does not sufficiently steer the efforts of stakeholders (Garske and Ekardt, 2021) and cannot ensure complete integration with climate goals (Kanter and Brownlie, 2019). These factors should urge us to think how alternative framings of phosphorus governance can be

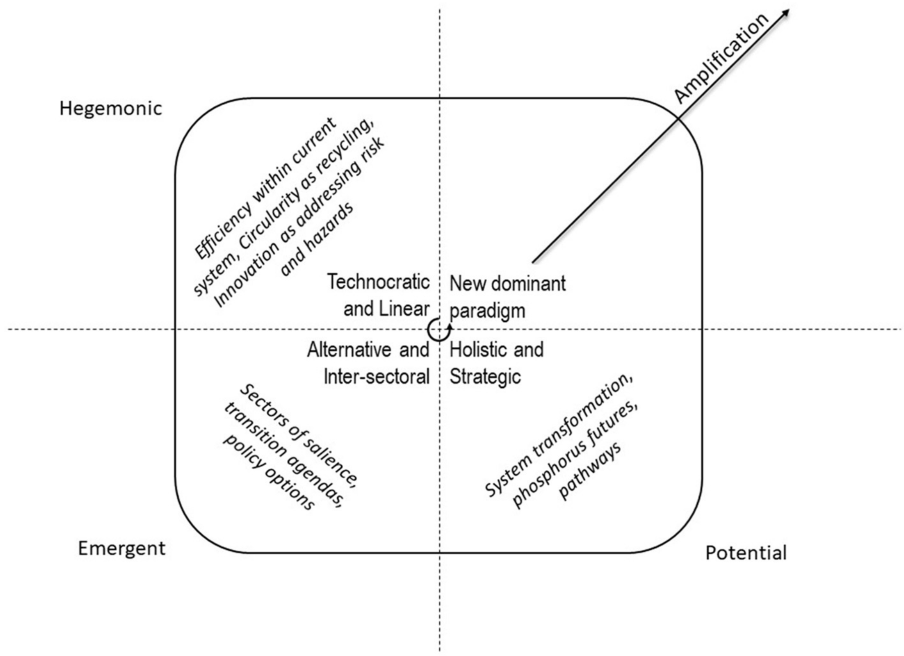

FIGURE 3
Typology of framings in P governance.

elevated onto the policy-making agenda of the EU so that socio-political challenges associated with phosphorus use are better addressed.

5 Conclusions

Although a well-researched academic field, phosphorus scholarship is trapped by excessive technicality and compartmentalization, which has produced siloed, short-sighted and slowly updating governance, incapable of addressing the socio-political challenges related to the use of phosphorus. Since the main source of phosphorus, phosphate rock, is a vital non-renewable natural resource that permeates different sectors, governance levels, materials and social relations, phosphorus governance can be described as a wicked non-renewable resource problematic that branches out into a complex system of siloed knowledge sub-systems. This siloed thinking is reflected in the vast number of EU regulations and policies that are at the same time narrowly limited to discrete aspects and sectoral uses of phosphorus, which are dominated by the sectors of agriculture and resource recovery. The resource efficiency paradigm, which permeates into many aspects of policymaking, maintains a linear vision of producing more with less. It is inherited as an incomplete and obsolete understanding of the circular phosphorus economy, which formally addresses phosphorus almost exclusively as a pollutant. This lock-in crowds out possible governance priorities, such as quantifying the true value of primary and secondary phosphorus or prioritizing virgin phosphorus for a small number of sectors, while directing the recovered material into sectors where experimentation is possible. Governing phosphorus as an inefficiently applied pollutant can produce paradoxical rebounds beyond the formally regulated sectors and polities. Even though phosphorus is of strategic importance to multiple economic sectors and their transitions, it has been primarily regulated as a polluting substance since 1972. Such path-dependent goal setting cannot be expected to generate system-wide transformations and create resilience to system shocks.

Because of these hegemonic views, the discursive possibilities for transforming phosphorus governance that may be situated across economic sectors and their transition agendas or encompass multiple priorities in a holistic way should be explored and highlighted as emergent alternatives. To increase their transformative potential, such framings may need to be identified through the strategic priorities in the EU. This may encompass the creation of more than one policy pathway, as well as selective amplification of the one(s) that may benefit from large-scale societal processes. In other words, to overcome the existing limitations, phosphorus governance should become more encompassing, holistic and integrative and be equipped with the potential to amplify emergent discursive framings that can enhance its political salience, embed it high on transition agendas and provide system directionality through policies that are in line with sustainability requirements. This can be defined as a process (that we exemplify in Figure 3) consisting of four steps associated with the quadrants: (1) identifying existing framings, (2) exploring alternative framings, (3) supporting the transformative potential of holistic and strategic framings, and (4) subverting existing framings to be amplified through socio-political processes. In view of the relevance of many social science disciplines in assisting policy debates, a new research agenda for phosphorus that makes productive use of discursive conflicts through an analysis of material agency, power and vested interests should provide a promising path to transforming phosphorus governance.

Lessons from such a social sciences-focused research agenda for phosphorus will likely have broader implications for the framing of other non-renewable resources competing for essential and strategic uses.

Author contributions

TK: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing—original draft, Writing—review & editing. MF: Conceptualization, Supervision, Validation, Writing—review & editing. BJ: Conceptualization, Funding acquisition, Supervision, Validation, Writing—review & editing. JMO: Funding acquisition, Validation, Writing—review & editing, Conceptualization, Project administration, Supervision. DC: Funding acquisition, Validation, Writing—review & editing.

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Supplementary material

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