Article:
Raniro, H.R. orcid.org/0000-0002-5041-8101, Serrano-Gomez, J., Mort, H.L. orcid.org/0009-0000-7330-7351 et al. (23 more authors) (2025) Overcoming recycling barriers to transform global phosphorus management. Nature Reviews Earth & Environment. ISSN: 2662-138X

https://doi.org/10.1038/s43017-025-00717-3

Overcoming recycling barriers to transform global phosphorus management

Henrique Rasera Raniro[1*], Juan Serrano-Gomez[2,3*], Harrie L. Mort[4], Teodor Kalpakchiev[4], Josephine Kooij[5], Yudong Zhao[6], Rodrigo M. Valença[7], Sinoxolo Magaya[8], Ana J. Guerrero-Esquivel, Leon Korving[9], Philipp Wilfert[10], Thomas Prot[9], Julia Martin-Ortega[4], Dorette S. Müller-Stöver[5], Mark van Loosdrecht[10], Dana Cordell[11], Jakob Santner[1,12], Henrikki Liimatainen[6], Ludwig Hermann[2], Matthew Scholz[13], Morten L. Christensen[7], Frederik van der Bom[14,15], Nelly S. Raymond[16,15], Søren Krogh Jensen[17], Fiona Smith[18], Kasper Reitzel[19†]

[*]These authors contributed equally: Henrique Rasera Raniro and Juan Serrano-Gomez
[†]email: reitzel@biology.sdu.dk)

[1]Institute of Agronomy, University of Natural Resources and Life Sciences, Vienna, Tulln an der Donau, Austria

[2]Proman Management GmbH, Auersthal, Austria

[3]Department of Civil Engineering, Technische Universität Wien, Vienna, Austria

[4]Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, UK

[5]Department of Plant and Environmental Sciences, University of Copenhagen, Frederiksberg, Denmark

[6]Fiber and Particle Engineering Research Unit, University of Oulu, Oulu, Finland

[7]Department of Chemistry and Bioscience, Aalborg University, Aalborg, Denmark

[8]Department of Environmental Geography, Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands

[9]Wetsus, European Centre of Excellence for Sustainable Water Technology, Leeuwarden, The Netherlands

[10]Department Biotechnology, Delft University of Technology, Delft, The Netherlands

[11]Institute for Sustainable Futures, University of Technology Sydney, New South Wales, Australia

[12]Institute for Plant Nutrition, Justus Liebig University Giessen, Giessen, Germany

[13]Global Futures Laboratory, Arizona State University, Tempe, AZ, USA

[14]Department of Plant and Environmental Sciences, University of Copenhagen, Taastrup, Denmark

[15]School of Agriculture and Food Sustainability, The University of Queensland, St Lucia, Queensland, Australia

[16]Department of Geosciences and Natural Resource Management, Geography, People and Processes, University of Copenhagen, Copenhagen, Denmark

[17]Department of Animal and Veterinary Sciences, Aarhus University, Tjele, Denmark

[18]UK Trade Policy Observatory and Sussex Law School, University of Sussex, Falmer, Brighton, UK

[19]Department of Biology, University of Southern Denmark, Odense, Denmark

Abstract

The global phosphorus challenge arises from the uneven distribution of phosphorus resources, environmental impacts from phosphorus losses and unsustainable linear management. Despite progress in advanced phosphorus recycling, less than 1% of secondary phosphorus resources produced globally are recycled. In this Review, we comprehensively explore global barriers to phosphorus recycling. Manure (15–20 Mt P yr^{-1}), mining and fertilizer industry waste (6–12 Mt P yr^{-1}), wastewater (~3.7 Mt P yr^{-1}) and food waste (~1.2 Mt P yr^{-1}) are the major secondary phosphorus resources worldwide. In addition, accumulated legacy phosphorus in soil and sediment comprises a combined stock of more than 3,200 Mt P. Phosphorus mismanagement and losses cost stakeholders US$265 billion yearly, yet substantial barriers to phosphorus recycling remain. Key challenges to be overcome include low competitiveness of recycled phosphorus products, complex waste handling, limited legacy phosphorus recovery and fragmented collaboration among stakeholders. A shift is needed toward an integrated, systems-based approach that simultaneously addresses technical, economic and societal challenges. Transdisciplinary strategies and research will advance phosphorus recycling and development of a sustainable, circular phosphorus economy. Incorporating the perspectives of diverse stakeholders will help drive increasingly sustainable phosphorus management.

Key points

- Mineral phosphorus dependency, uneven global distribution, eutrophication and linear nutrient management are fundamental and deeply interconnected challenges in managing phosphorus.
- Efficient phosphorus use and recycling are essential to closing the phosphorus cycle, but numerous barriers stand in the way of achieving this goal.
- Conflicting objectives among stakeholders is a key barrier to developing and implementing effective strategies for sustainable phosphorus use.
- Successful strategies for circular management of phosphorus require improved communication, interdisciplinary research, and transdisciplinary processes that incorporate the needs of all stakeholders.
- Inclusive policies are vital to align incentives, foster collaboration and promote sustainable phosphorus-use practices.

[H1] Introduction

Phosphorus (P) is crucial for supporting food and industrial production worldwide. Global P demand currently totals 26.5 Mt P yr^{-1}, driven by food production (~80% for fertilizers and 6% for food additives) and industrial applications (14%)[1,2]. Most consumed P originates from phosphate rock[3,4], a finite resource with known high-quality reserves that are expected to be depleted within the next few centuries[5]. In addition, more than 85% of global P deposits are concentrated in just five countries, limiting equitable access to this critical resource, particularly during periods of geopolitical uncertainty[6,7]. Furthermore, 80–95% of all mined P is lost owing to inefficient P management[8,9]. Much of this loss occurs on farmers' fields, where unconsumed P from past inputs accumulates as legacy P in soil or freshwater sediment. Excess P in aquatic environments causes severe environmental damage. Globally, P mismanagement costs stakeholders approximately US$265 billion annually (ref.[6]).

In response to these sustainability, equity and environmental challenges, efforts to establish a circular phosphorus economy are gaining momentum[10]. For example, China is reducing P waste streams by using industrial sludge as fertilizer[11]. Brazil's National Fertilizer Program is diminishing P inputs in agriculture and reliance on imports by establishing governance and monitoring tools, promoting research and innovation and exploring domestic sedimentary phosphate basins[12,13]. The European Union's Circular Economy Action Plan[14], adopted in 2015, provides an initial framework for nutrient recycling within its territory. Globally, the potential for P recycling is huge, with the amount of P trapped annually in recyclable resources comprising 143% of the current (2024) yearly P demand[1].

Cascading innovations are focused on the recovery of P from diverse waste streams. The economic, societal and environmental benefits of P recovery[15], the potential of secondary sources of P to partially substitute mineral P in the production of fertilizers[16,17] and a role for recycling in closing nutrient loops[18] highlight the importance and advantages of P recycling. Concurrently, technological breakthroughs have facilitated the transition of large-scale operations to the use of secondary P in manufacturing industrial products[16,17]. Despite notable progress in infrastructure[19,20], policy development[21,22] and recycling technologies[17,18] for circular nutrient management, challenges in P management persist. Contextual differences, disciplinary fragmentation and limited stakeholder coordination hinder the development of well-defined pathways to achieve greater phosphorus circularity worldwide[10,23], reflecting its nature as a wicked problem.

In this Review, we explore the reasons why P recycling from secondary sources remains limited. We discuss a range of technical, economic and societal barriers to global P recycling[24–26] and argue that fostering transdisciplinary collaborations is essential to improving P sustainability worldwide, precisely because such collaborations are best positioned to align the diverse interests of stakeholders across sectors and disciplines.

[H1] The need to improve phosphorus management

The ideal P value chain is circular, but in practice it is predominantly linear. The cycle begins when P mined from phosphate rock is used to produce fertilizers and other goods. After manufacturing, P is consumed by humans, crops or animals, but substantial amounts of P are lost to secondary P waste streams at every stage of the P life cycle. Phosphorus losses to the environment are also pervasive, leading to P accumulation in soil and sediment, where it can contribute to environmental degradation[8,27–29].

Furthermore, as access to phosphate rock reserves diminishes, both economically and geographically, the risks to global food production also rise[30,31]. These challenges highlight the need to develop strategies for recovering and recycling P. The EU has some of the most advanced technology, data availability and legislation relating to P recycling, yet, even in the EU, the P cycle remains essentially linear (Fig. 1).

[H2] Geopolitical dependence on primary phosphorus imports

Most regions worldwide rely heavily on P imports from a limited number of countries (Morocco alone contains ~67% of the world's known reserves[2,32,33]), creating pronounced geopolitical vulnerabilities in food security [34,35]. Political, economic and environmental disruptions can lead to global price shocks[35]. For example, in 2008, phosphate fertilizer prices spiked by 800%, mostly due to rising energy costs and geopolitical trade policies[36], generating supply constraints and threatening agricultural production and food security in several parts of the world[37,38]. More recent supply chain disruptions include the COVID-19 pandemic[39], the Ukraine-Russia conflict[40], reductions in P fertilizer exports by China and Russia[34,41], and trade wars between key stakeholders (such as China and the USA[42]). The negative impacts of these events disproportionately affected countries in Africa[43]. Asymmetric risks associated with primary P dependence underscore the need for diversified P sources and more resilient supply chains.

[H2] Agricultural needs and phosphorus wastage

Approximately 90% of all mined P resources are used in fertilizers[44,45], and global P use since the Green Revolution has increased more than six-fold[1,46]. However, quantifying global P flows and stocks is challenging owing to major regional differences in P resource availability, prices and efficiency of use, all of which are shaped by economic, political and environmental factors[10,46]. The most comprehensive accountings of European and global P mass describe conditions in 2005[47] and 2009[38], respectively. Both assessments highlight increasing agricultural demand and pervasive losses throughout the P life cycle.

Where intensive agricultural practices coincide with widespread access to mined P resources, high P input and legacy P often result[48]. China and Brazil use substantial amounts of mineral fertilizer (more than 32 kg P ha^{-1} of cultivated land yr^{-1})[48] as P input compared with 5–10 kg P ha^{-1} yr^{-1} of manure, and P removal through crop harvests is also high (24 and 26 kg P ha^{-1} yr^{-1}, respectively). Conversely, the low agricultural productivity in most African countries is partially attributed to low P input[49] (Fig. 2).

Most European countries have moderate or low mineral fertilizer inputs (0–16 kg P ha^{-1} yr^{-1}) and moderate or high manure inputs (8–24 kg P ha^{-1} yr^{-1}), except for the Netherlands and Belgium, where manure application is remarkably high (65 and 35 kg P ha^{-1} yr^{-1}, respectively). In the USA, mineral fertilizer application is moderate (8–16 kg P ha^{-1} yr^{-1}), manure input is low (0–8 kg P ha^{-1} yr^{-1}) and crop removal is moderate (8–16 kg P ha^{-1} yr^{-1})[48]. Importantly, P losses are extensive almost everywhere. For example, the terrestrial P surplus (that is, P that was applied to fields but not exported by crop harvest) in the USA in 2012 is estimated at 1.85 Mt P, with many agricultural areas exhibiting high surpluses, particularly in the upper Midwest[50].

[H2] Environmental impact of phosphorus mismanagement

Phosphorus mismanagement results in massive environmental degradation. Some mismanaged P ends up in water bodies and causes eutrophication[51,52], resulting in harmful algal blooms, dead zones and biodiversity loss. Annually, approximately 1.5 Mt of anthropogenic P are lost to freshwater systems[53]. The EU released a Water Framework Directive more than 25 years ago[54], yet 60% of lakes in the region do not meet the directive's 'good' standard. Pervasive eutrophication and ineffective water restoration highlight the urgent need to rethink P use practices and develop sustainable P management solutions.

By recovering P from nutrient-rich waste streams, such as wastewater and animal manure, using methods such as chemical precipitation, advanced composting and biochar production, P recycling from agricultural systems can be increased[1,17,31]. Furthermore, recovering recalcitrant P stocks in soil and sediment can be crucial to ensuring global P circularity.

These geopolitical, wastage and environmental aspects reveal a global P landscape marked by stark regional contrasts, ranging from over-application and environmental losses to chronic underuse owing to limited access to P resources. Addressing these imbalances is essential to improving agricultural productivity and the sustainability of P use worldwide.

[H1] Recovery of secondary phosphorus

Improving P circularity is indispensable to overcoming the geopolitical, agricultural and environmental challenges associated with P mismanagement[8,10]. Achieving this goal requires optimizing the use of primary P resources (mined phosphate rock), utilizing P stocks accumulated in soil[27,28] and sediment[55], and enhancing P recycling from P-rich secondary sources, including waste from the mining and fertilizer industries[1,56], livestock manure[16], wastewater and sewage sludge[57,58] and food waste[59] (Table 1).

[H2] Mining and fertilizer industry waste

The mining industry produces substantial amounts of secondary P contained in byproducts and waste from rock mining (1.1–3.0 Mt yr^{-1}), and phosphoric tailings generated during rock beneficiation (2.3–4.6 Mt yr^{-1}), which together represent 12–16% of total P mined globally[2,9]. Although P recovery from mining waste using pyrolysis, leaching and precipitation have been proposed, these approaches are complex and expensive[60,61], and large-scale recovery is currently not viable[62]. Typically, mining waste is landfilled, and usually covered with vegetation to reduce environmental risks such as erosion, dust production and P runoff.

The fertilizer industry also generates P-rich waste such as P slag (~1.8 Mt P yr^{-1}) and ferrophosphorus (~0.3 Mt P yr^{-1})[1]. In addition, ~300 Mt of phosphogypsum (containing 6–9.8 Mt P) is produced annually by acidifying phosphate rock[1,63]. Although phosphogypsum has agronomic applications, 58% is landfilled[64] and 28% is discharged into the sea[65], comprising a global stockpile of 60–160 Mt of P[56,65], of which only 14% is further treated[56].

[H2] Livestock manure

Livestock manure is the largest secondary P resource (15–20 Mt P yr^{-1})[1,47], accounting for more than 50% of the annual secondary P generated worldwide. In the EU, ~2.2 Mt P yr^{-1} comes from manure, of which ~90% is directly applied to agricultural land[16,66,67]. However, a substantial portion of manure is difficult to recover because grazing animals deposit it directly onto grasslands[67]. Intentional application is often concentrated near livestock production areas, serving more as a means of waste disposal than as a targeted agronomic strategy[16]. This practice can lead to the accumulation of soil legacy P. Moreover, manure typically has a low N:P ratio, which can contribute to P overapplication as farmers prioritize addressing crop nitrogen requirements. In China, ~2.14 Mt P yr^{-1} from manure is applied on agricultural land[68], representing 26% of the country's total P demand, but this is only ~50% of the P that could be harnessed from manure in China[69].

Owing to the low P concentration in manure (<1% of P per fresh weight), concentrating P from this source can improve P recovery and subsequent recycling, thereby facilitating efficient handling, transportation and application[16,67]. The water content and volume of manure can be reduced using non-thermal methods, such as flocculation, settling, screw pressing, belt filtration centrifugation, and dissolved air flotation after anaerobic digestion[70,71], but technical, logistic and financial challenges remain.

Biogas production from manure is common in developed countries, yielding a digestate containing ~2% P[72]. To further concentrate P in fresh manure and its digestate, solid–liquid separation techniques have proved effective[73]. About 70–75% of P can be recovered in the solid fraction without flocculation, whereas flocculation increases the recovery rate to 80–90%.

[H2] Food and biorefining wastes

As much as 1.2 Mt P could be recycled annually from farming, food manufacturing, biorefining, and consumer wastes and byproducts[1]. However, resource heterogeneity complicates recycling from food waste[25]. Recovery techniques such as composting, anaerobic digestion and fermentation are the most common strategies for nutrient recovery from food waste. Other methods, such as incineration, are promising, but come with their own drawbacks such as increased pollution[59,74].

Industrial food manufacturing is a major source of food waste, accounting for almost 50% of the food waste in the entire supply chain in the UK[75]. This waste often takes the form of useful materials such as whey and starch residues[75]. Meat and bone meal (a slaughterhouse byproduct) has high P content (3–5%) and are already used as a P fertilizer in some countries, but concerns about pathogen risk and public perception still limit its use in other countries[76].

Biorefinery residuals, such as waste from bioethanol production or breweries, are also rich in P. A prominent example is distillers' dried grains with solubles, a byproduct of corn ethanol production, of which ~38 Mt yr^{-1} is produced in the USA alone. With a typical P concentration of ~1% of dry weight[74,76], this amounts to ~0.38 Mt P yr^{-1}, making it one of the largest flows of concentrated organic secondary P in North America[77]. Although commonly used in livestock feed, which aids P recycling to some extent, the spatial disconnect between production and consumption sites requires complex transport logistics and high costs, often resulting in ineffective P recovery[77].

Post-consumer food waste, primarily from households and the food service industry, is the largest global food waste stream, amounting to ~570 Mt annually[78]. This waste is typically heterogeneous and often contaminated with plastics or packaging residues[79], posing major logistical and regulatory challenges for safe reuse[80]. In Barcelona, compost derived from household food waste is applied to urban agriculture plots, but contamination and legal hurdles intended to lower the risk of contamination limit broader nutrient recycling efforts[80]. Another example is seen in Thailand, where food waste composting and direct use as animal feed recovered up to 71% of the P content in food waste from retail and wholesale markets[81]. Despite its potential, P recovery from food waste remains underdeveloped, partially owing to severe logistical, environmental and behavioural challenges, low economic incentives and weak regulatory enforcement[74,76].

[H2] Wastewater

Wastewater refers to water discarded from households, businesses and industries, as well as stormwater runoff. Globally, ~360 billion m^3 of wastewater are produced annually, containing 3.7 Mt P[82,83]. However, in current market conditions, the economic feasibility of P recycling from wastewater remains limited[83], so most wastewater treatment plants prioritize meeting discharge requirements for treated wastewater rather than actively recovering P[23]. P is typically removed from wastewater through chemical, biological[84] or combined treatment methods[85], with ~90% ending up in sewage sludge[86].

Sewage sludge is sometimes applied directly to agricultural fields[87]. However, this practice is being increasingly restricted owing to concerns about contaminants, including heavy metals, pathogens, microplastics and toxic organic compounds. Although only a small fraction of P from wastewater is recovered using advanced recovery methods[88], the potential of numerous technologies has been demonstrated at full or pilot scale[88,89], particularly in North America, Europe and Asia. For effective recovery, P must first be dissolved and then concentrated and recovered through precipitation, crystallization or adsorption[89]. Typically, sludge liquor, sludge or sludge ash are used to produce P-recovered products such as struvite, calcium phosphate or phosphoric acid[90].

Recovering P directly from sludge tends to yield lower-purity struvite (with lower P and higher impurity concentrations), whereas recovery from the water separated from sludge generally produces a higher-quality product and higher yield, but combined, these methods only capture 10–40% of influent P[17]. High recovery yields, ranging from 60–70%, can be achieved through vivianite precipitation[90] or sludge acidification, followed by solid–liquid separation and precipitation[91]. However, these processes are energy-intensive and thus contribute to global warming, and they require substantial amounts of acid[92]. Although the P recovery efficiency is higher than for struvite-based technologies, these methods have yet to progress beyond pilot-scale demonstrations[90].

High yields of micropollutant-free P, typically 80–90%, can also be recovered from sludge ash[89]. Current technologies for P extraction from sludge ash can be categorized as wet-chemical, thermochemical and electrodialysis methods[93]. These methods vary in their effectiveness in heavy metal removal, emissions production and energy demands[92]. P extraction from sludge ash can recover high volumes of P, making centralized facilities feasible. Other methods, such as pyrolysis or hydrothermal carbonization, produce char that can be used directly on agricultural fields, if inorganic and organic pollutants are below local legal thresholds[93]. Despite the high potential for P recovery from wastewater and its byproducts, only 61 facilities worldwide currently pursue advanced P recovery that goes beyond conventional sludge recycling or land application of biosolids, collectively recovering ~4.2×10^{-3} Mt P yr^{-1} from secondary sources[88] ([H1] 3). High capital expenditure requirements hinder investment in these promising technologies[17,89].

[H1] Legacy phosphorus

In agriculture, P input through the application of mineral and organic P fertilizers often exceeds the amount absorbed by crops, resulting in a gradual accumulation of legacy P in the soil[27,28]. Most legacy P is strongly bound to the soil matrix, primarily to inorganic soil constituents, or is lost to aquatic environments through erosion, runoff or leaching[48,55], eventually accumulating legacy P in sediment[28,55,94], where it often contributes to environmental issues, such as eutrophication. Although legacy P is often not immediately available to plants, physical, chemical and biological pathways exist that can mobilize this P, allowing a portion of legacy P to be taken up by crops in the future[95].

[H2] Legacy phosphorus in soil

Globally, excessive fertilizer use between 1965 and 2007 resulted in the accumulation of over 815 Mt of legacy P in the soil[96]. The high reliance on P fertilizers is particularly evident in Western Europe, Brazil, North America and Asia, where anthropogenic P accounted for nearly 60% of the available soil P in 2017[97]. By contrast, Africa relies on these P inputs for only approximately 30% of the total available P in the soil[98]. Although P fertilization is projected to rise from 20 Mt P in 2023 to 22 Mt P in 2025[2], only ~30% of the P supplied to crops is absorbed in the year of application, and ~45% becomes legacy P[29] (the remaining 25% is lost through erosion, runoff, and leaching). For example, soil legacy P was ~9 Mt in 2023[48] . In the

EU, excessive fertilizer use has led to an accumulation of ~222 Mt of legacy P in topsoil[66], and legacy P accumulated in agricultural soil could reach ~107 Mt by 2050 in Brazil[29].

Efforts have been made to utilise or 'mine' soil legacy P. One promising approach is cover cropping with species that are capable of accessing less-available forms of P[99] through adaptations such as altered root structures and architectures[100], high rhizosphere acidification capacity[101] and increased root exudation of compounds such as phosphatases and carboxylates that enhance P mobilization and availability[102]. The biomass of cover crops is then incorporated into the soil, where it releases bioavailable P that can be used by subsequent crops[99]. Bioengineering and breeding crop varieties with higher P mobilization potential are also being investigated[103,104]. However, these approaches are complex and heavily influenced by specific environmental conditions and soil P status[105], which can limit their reliability. Furthermore, newly dissolved P resulting from the effects of freeze–thaw cycles on cover crop biomass can reach nearby waterways[106].

Biostimulants are another promising strategy for mobilizing legacy P[107]. These substances alter the soil microbiota or promote P scavenging by roots to enhance crop P uptake[108]. Biostimulants work by mobilizing relatively stable forms of P into plant-available forms, which can considerably increase the efficiency of P use in agricultural systems, particularly in soil with high legacy P levels.

[H2] Legacy phosphorus in sediment

Historical P loading from wastewater, runoff and erosion from agricultural soil has led to the accumulation of ~2,686 Mt of legacy P in aquatic sediment, with an estimated current accumulation rate of 1.5 Mt P yr^{-1} [55]. Waterbody management practices focus on maintaining or restoring water quality by immobilizing P in the sediment, which is typically achieved by adding P-binding agents or aerating lake water to promote the binding of P to iron in sediment[109]. Although these practices reduce P reactivity and mitigate potential environmental damage, they do not facilitate P recycling. By contrast, reusing lake sediment[94] or filtering and recycling P-rich lake water would help to achieve P circularity.

Despite the substantial P stock in sediment, exploiting this resource by recycling P faces notable challenges that hinder its feasibility. The P recovery process involves complex and costly steps, including dredging, flocculation and dewatering of sediment[110]. Then, the treated sediment must be transported and applied to agricultural soil, which adds new layers of complexity, expense and risk if the sediment contains contaminants. Although using P in sediment holds promise and could contribute to P supply, more research and technological development are needed to overcome these hurdles.

[H1] Barriers to phosphorus recycling

In Europe, China, Japan and North America, financial capacity is adequate for developing and deploying efficient P recycling technologies[10,11,25,31]. However, numerous interconnected barriers pose considerable challenges to implementing efficient P recycling (Fig. 3). These obstacles also increase reliance on imported mineral phosphates, exacerbating geopolitical and environmental vulnerabilities. Acknowledging the interconnectedness of these barriers underscores the need for transdisciplinary approaches, where diverse sectors (including academia, industry, consumers, farmers and others) collaborate to develop comprehensive and sustainable solutions for P management and recycling.

[H2] Technological barriers

Developing P-recycling capabilities is the most apparent technological challenge. The heterogeneity of secondary P resources complicates technology transfer between waste streams. For example, P-recovery technologies designed for wastewater are not easily adaptable to recovering P from manure or lake sediment, owing to different requirements regarding removal of pollutants, pathogens and contaminants[111]. Furthermore, some recycling methods can separate contaminants from waste but often result in poor P recovery or reduced P availability. The best available techniques for recovering P, such as incineration, pyrolysis, thermochemical processing and electrodialysis, are typically chemically intensive, operationally complex and costly[112,113], and all yield products that have downsides, notably low P bioavailability without further chemical processing[17], and the continued presence of some heavy metals and other pollutants.

Nonetheless, various P recovery technologies are available and are increasingly being implemented at full scale[88]. The challenge lies in balancing treatment costs with performance. Ensuring high P recovery rates from secondary resources while producing clean, safe and highly efficient fertilizers remain difficult to optimize simultaneously.

A less obvious technological barrier relates to the production of knowledge. Standardized analytical methods for assessing P availability do not effectively characterize highly complex, heterogenous products[114,115]. Worse yet, no standardized method for P speciation (the chemical forms in which P exists) in recovered products currently exists, although X-ray diffraction is often used. Although effective for identifying mineral P forms, this method is unsuitable for detecting organic P, is inherently qualitative, and fails to provide accurate results when mineral phases are poorly crystalline or amorphous.

These data are crucial for generating, evaluating and comparing the efficiency of recovered P sources, relative to conventional fertilizers[115,116]. Furthermore, the heterogeneity and complex chemical composition of secondary P resources hinder their evaluation as fertilizer alternatives. For example, in the Netherlands, increasing amounts of macerated food waste are being diverted to sewage systems, contributing to mixed flows being treated in wastewater treatment plants[117]. This practice blurs the line between household and municipal waste streams, complicating the traceability and purity of recovered P.

[H2] Knowledge barriers

These technical barriers result in knowledge barriers: gaps in understanding of the dynamics of recycled materials in the environment and their efficiency as fertilizers. For example, lack of knowledge of P availability and speciation hinders developers of models for improved P management and regulators, who need these data to proceed sensibly. Recycled products often have lower water solubility and slower P dissolution dynamics than conventional mineral P fertilizers, but can release similar amounts of P over longer periods[118] and achieve similar agronomic efficiency[119,120]. However, the long-term effects of continuous use of recycled fertilizers are still mostly unknown. The characteristics, production process, application method and environmental risks of the various recycled P sources are not sufficiently understood to anticipate how they will affect fertilizer performance and the environment over time[16,121]. Therefore, understanding the dissolution kinetics and overall behaviour of recycled fertilizers in different environments is essential for modelling their transport in fields and watersheds.

In addition, the complex interplay between soil partcicles (such as Fe and Al oxyhydroxides and clay minerals) and the P in fertilizers is not sufficiently understood. Phosphorus phytoavailability and legacy P accumulation rates vary considerably. Although slower fertilizer solubilization can be advantageous in acidic soil, improving crop uptake and reducing leaching and runoff, P release from biochar and struvite, for example, is considerably delayed or reduced in alkaline soil, and therefore is potentially too slow for optimal plant growth[122,123]. Furthemore, soils with high P sorption capacity, such as those rich in iron and aluminium oxides, can tightly bind P, increasing soil legacy P, whereas sandy or organic-rich soils often retain less fertilizer-derived P, promoting higher bioavailability.

Current understanding of mineral-bound P species is uneven. Whereas iron phosphates have received increasing attention over the past decade, particularly those precipitated from sewage sludge, research on aluminium-P forms, which is also highly utilized for P precipitation in wastewater treatment plants, remains underexplored. This gap limits the development of P-recovery processes from aluminium-rich waste streams and further complicates efforts to assess the potential and limitations of different recycled P sources in a comparative, system-wide manner.

These knowledge gaps complicate the accurate measurement of P circularity. For this reason, the true economic, environmental and climate-related impacts of failing to recycle P are still not fully understood. These uncertainties impede wider adoption of recycled P alternatives, even by early adopters[88]. Without sufficient production, potential users cannot fully test P sources in real production scenarios, which raises concerns about their effectiveness in agricultural systems. This uncertainty lowers farmer demand, which lowers profit expectations for producers, thereby further hindering effective P recycling[23,124].

[H2] Logistics-related barriers

Logistical barriers refer to obstacles that impede the collection, handling, processing and redistribution of waste streams and recycled P. A notable logistical challenge is the distance between the sources of recycled P and arable land where it is needed. For example, densely populated areas generate substantial amounts of P-rich wastewater, but these regions are frequently far from agricultural lands that require P inputs[66]. For example, in the Netherlands, sewage sludge application on farmland has been banned since the 1990s owing to concerns about contaminants. Following an incineration capacity shortfall in 2020, the Netherlands exported 27.5 kt of sewage sludge to the UK, one of the few nearby countries that still permit land application of treated sludge[125]. Besides being logistically difficult, this trade was economically impractical, resulting in a financial loss.

Regional generation and distribution imbalances are an issue with the use of manure[16,67,126]. The high volume and moisture content (85–95%) of manure create logistical challenges for its handling, storage and long-distance transport[127–129]. The water content of manure can be reduced, thereby increasing P concentration, but logistical shortcomings continue to limit the accessability of manure for P recycling[130,131]. Existing techniques such as thermal drying can reduce moisture content to 10–15% but are expensive and energy-intensive[132]. The use of more accessible, non-thermal techniques results in a product with 65–75% water content, which is still too high for efficient, cost-effective application and transportation. In Sweden, if fertilizer prices remain stable and recycling processes are unchanged, transportation costs would need to be reduced by 73% for manure recycling to be cost-effective[133].

Last, recycled P fertilizers are cumbersome, complicating their application[129,134]. Recycled P fertilizers are often bulky or dusty, which makes them difficult to handle and requires specialized and/or multiple machines to manage large volumes. For example, although food-waste-based compost and digestate can improve soil structure and organic carbon content, their P content is low (~0.4% P on a dry matter basis[25,76]). As more concentrated P fertilizer options exist, farmers resist extra investments that would facilitate the use of more bulky, recycled options. In addition to P, recycled fertilizers can contain variable nitrogen, potassium and micronutrient content, and this variability, coupled with differing nutrient-release dynamics and logistical costs, tends to dissuade farmers from using recycled products[135].

[H2] Economic and financial barriers

The economic feasibility of safely recovering and using P from secondary sources is another barrier to P recycling[136]. High initial investments, elevated production costs and uncertain returns deter the implementation of P-recovery technologies[23]. The financial magnitude of full-scale P recycling from sewage sludge ash into technical-grade phosphoric acid (75% H_3PO_4, containing 23% P) has been demonstrated in Switzerland. As of 2023, the projected capital expenditure for a facility producing 40 kt of technical-grade phosphoric acid annually is ~US$190 million, with operational costs of ~US$29.5 million yr^{-1} to produce 12 kt of phosphoric acid annually (2,760 t P yr^{-1}). Thus, operational costs are ~US$2,460 t^{-1} of phosphoric acid and annualized capital expenditure is ~US$9.3 million (~US$775 t^{-1} of phosphoric acid) [137]. At the time, the market price of phosphoric acid was below US$1,100 t^{-1}, about three times less than the production cost of recycled phosphoric acid[137,138].

The higher cost of recycled P fertilizers is related to the physicochemical characteristics of the secondary materials, the smaller operation size (economy of scale) and the increased complexity of most recovery processes[137]. For example, advanced P recovery from manure yields a final product that is too expensive for most farmers, compared with raw manure[16]. Similarly, fertilizers produced with struvite precipitation technologies can be 2–14-fold more costly than those derived from phosphate rock[17,139,140]. Most attempts at struvite precipitation (related to clogged pipes from uncontrolled struvite crystallization) have been motivated by an interest in reducing maintenance costs, not in producing fertilizers[141,142]. The higher cost of recycled fertilizers compared with those from conventional sources and their uncertain benefits in terms of crop yield can considerably discourage farmers from using recycled materials[140].

Phosphorus recycling is also markedly influenced by global economic disparities. For farmers, who often even struggle with the cost of conventional fertilizers, investing in recycled P sources is risky, with an uncertain and potentially delayed return on investment[143,144]. This scenario leads to reluctance in committing resources to adopt recycled alternatives, hindering P recycling implementation in developing regions[18,145].

[H2] Societal barriers

Societal barriers encompass poor food planning, misinterpretation of 'best-before' dates for perishable foods, and over-purchasing, all of which are core contributors to household waste[78,79]. Furthermore, perceptions of recycled fertilizers, including their safety, can lead to acceptance-hindering stigmas, including concerns about contaminants and pathogens, as well as 'yuck factors' such as odour[146,147]. These perceptions can discourage farmers from embracing recycled fertilizers and deter consumers from buying produce grown with them[136,148]. In addition, farmers often resist shifting from established practices that they know are effective[135]. They know that recycled fertilizers release nutrients more slowly but are uncertain about the implications of this difference. Their hesitance is exacerbated by a lack of expert advice and guidance that is tailored to their specific situations, leaving many farmers unsure about the most effective use of these products[149].

[H2] Regulatory barriers

Regulatory and legal barriers to P recycling are related to policies and legislation that fail to effectively support P recycling at various scales. Issues range from poorly focused regulations and guidelines for P use, management and recycling, the absence of quality assurance procedures, inadequate governmental incentives and lack of collaborative goal-setting[150], to the unexpected and adverse impacts on domestic P recycling of regulation designed to address 'unfair' agricultural trade policies at the international level[151]. All of these issues hinder the development of strategies and clear frameworks for P recycling globally[152].

Market access to recycled fertilizers is often impeded by existing subsidies for mineral P fertilizers, but incentives to adopt recycled products are also insufficient, perpetuating their low competitiveness[153]. These policies discourage the use of recycled products and limit their global trade potential, further stalling efforts to create a circular economy for P recycling. One notable regulatory barrier is the lack of authorization for using recycled fertilizers in agriculture. For example, countries such as China, Japan and the USA have made technological advances in P recovery from wastewater, but lack policies that actively support or require P recovery from the wastewater sector[58]. A major reason is quality concerns regarding products that are feared to contain heavy metals, pathogens, microplastics and toxic organic compounds, such as per- and polyfluoroalkyl substances (PFAS). These fears lead to regulatory and market barriers[80]. Only a few countries worldwide (that is, Germany[154], Austria[155] and Switzerland[156]) have implemented regulatory mandates for P recovery from sewage sludge[157]. This regulatory lag limits the widespread adoption of P-recovery technologies in many regions.

Similarly, up until the 2020s, legal approval for struvite to be used as a fertilizer was not forthcoming, but this use is gradually being accepted globally. In the EU, legislation is following this trend: an amendment of the Fertilising Products Regulation (EC2019/1009)[158] now enables the use of struvite as a fertilizer. However, other major P-rich secondary sources still lack approval. An example is Category 1 animal byproducts (animal parts suspected or confirmed to be infected by biological hazards), which can have high P concentrations, but are not currently authorized under the EU's Fertilising Products Regulation owing to health concerns. For example, there is a potential risk of contamination with prions that cause bovine spongiform encephalopathy, and despite certain thermal treatments and downstream acidulation showing certain efficiency in eliminating such risks[159], other studies are less conclusive[160] and the techniques lack validation at scale. More complex certification processes for these products place an additional burden on producers, who must ensure compliance to gain market access, and ultimately discourage P recycling[161].

There is a lack of harmony between the regulations and guidelines for different P-related sectors. Numerous sector-specific regulations exists for P management but there is no overarching governance framework[162]. For example, in the EU, the Fertilising Products Regulation (EC2019/1009) now includes recovered P fertilizers, but frameworks that regulate secondary P resources, such as the Urban Wastewater Treatment Directive 91/271/EEC[163], offer no guidelines about recovered P. Using manure or sewage sludge, farmers often apply the maximum nitrogen dose allowed by the EU Nitrates Directive (91/676/EC)[164,165], potentially resulting in P overapplication[67]. Although many EU Member States provide P application guidelines, relatively few have legislation focused on the use of P fertilizers[166]. This sectoral approach perpetuates technocratic objectives focused on narrow goals[22], relying heavily on command-and-control instruments that are weakly enforced. These hindrances result in a fragmented policy landscape that impedes the systemic adoption of P recycling practices[21].

The fragmentation in legislation is further exacerbated by stakeholders operating in disciplinary silos with a narrow focus on their specific concerns rather than collaborating to establish a holistic framework for P management[167]. For example, stakeholders concerned with contaminants in waste-derived fertilizers, such as environmental advocacy groups, or the general public concerned with the 'yuck factor' of these fertilisers, tend to advocate for strict regulations regarding P recycling without fully considering the economic challenges faced by farmers and wastewater companies[136]. These concerns highlight the broader challenge of determining when such materials can be considered safe to use, which complicates regulation and policymaking, a key issue in the ongoing 'End-of-Waste' debate. This dilemma points to the need for shared knowledge, open dialogue and a community-driven willingness to compromise in pursuit of more balanced and workable policies.

[H1] Strategies for moving forward

[H2] Improving phosphorus flows

Addressing the global P challenge requires a multifaceted, holistic approach that harnesses the expertise of individual disciplines[22]. The first pathway to better P management is to reduce the volume of secondary P. In agriculture, this approach includes developing precision farming techniques that increase application efficiency and reduce runoff to water bodies[168]. In addition, better manure recycling, and the integration of livestock and crop production, are needed to use manure more efficiently as a P fertilizer. In urban contexts, this approach includes decreasing food waste and broadening the collection and treatment of wastewater to recover P and reintroduce it into the cycle. P recovery through waste treatment should be expanded globally, with investments in infrastructure that support P recycling from agricultural, industrial and urban waste[169].

Increasing the recovery from secondary P resources must be complemented by reducing demand for P resources. Transformative changes in human diets and consumption patterns are essential to mitigate the impacts of P-intensive food production. Over the past 50 years, per capita P footprints have surged owing to dietary shifts, primarily rising consumption of meat, which now comprises 72% of the global P footprint. This shift has driven a 38% increase in global P demand between 1961 and 2007, with substantial variations across countries[170]. Reducing meat consumption, especially in countries with high P footprints, could substantially decrease P demand[170]. This change would both help conserve finite P resources and reduce the risk of eutrophication, thus aligning with broader environmental and health sustainability goals. In addition to dietary changes, improving P use efficiency and enhancing recycling at each stage of food production are crucial complementary strategies[170].

In addition to improved production, the challenges posed by the damage done by P that is lost to the environment remain. Technologies are needed to reduce P runoff into waterbodies. Lower P losses can be achieved by effective exploitation of legacy P in soil through intensive farming, cover cropping, biostimulant use and efficient P management (for example, fertilizer choice, application timing and doses). Waterbody restoration techniques should focus on recycling legacy P in sediment for use in agriculture. For example, restoring lakes through sediment dredging could provide P while substantially reducing methane emissions[171]. Therefore, tapping into P stocks in soil and sediment could help address both the P and climate challenges. Advanced P recycling can also play a major part in reducing both legacy P accumulation and losses to water bodies. Widespread P recycling would increase the market availability of less water-soluble fertilizers (such as struvite, (bio)chars and sludge ashes), decreasing reliance on water-soluble fertilizers that are prone to runoff[172]. In some cropping systems, this shift could better align P release with plant demand, reducing P fixation in soil and losses to water bodies[173].

Improving P use efficiency in animal feed can substantially reduce P losses across the agricultural system. One well-established approach is the addition of enzymes such as phytase, which increase P availability to animals, thereby lowering P additive to feed and therefore total P intake by livestock and reducing P concentrations in manure[174]. Another strategy is to remove excess P from feed ingredients. For example, in the USA, P is removed from dry distillers' grains used as feed to reduce its P content before consumption[77]. However, the need for more efficient use of manure remains. Once manure is produced, recovering P from digestate can further improve overall nutrient recycling[175]. Advanced P recovery from manure often involves solubilizing and precipitating P compounds such as calcium phosphate and struvite[176,177]. Emerging methods such as vivianite separation, vacuum evaporation, membrane filtration and ion exchange are promising[175] but not yet fully developed or widely implemented.

[H2] Policy and pricing instruments

Prescriptive regulations to reduce harmful practices, mandate P recovery[178] and enforce the use of recovered products are widely advocated[11,16,18] but not often implemented. This hesitance has spurred calls for broader approaches, including price-based policy instruments such as auction or tender systems that allocate public funds to support environmental services, and quantity-based mechanisms, including offset programmes[179]. The major challenge for any price-based incentive scheme designed to change P use at the country level is preparing for and responding to unexpected impacts from World Trade Organization (WTO) rulings regarding food production for export.

Under the rules of the WTO Agreement on Agriculture, pricing policies interpreted as 'market-distorting' are prohibited. Government policies that manipulate the price of P fertilizers might fit this description. Fortunately, exemptions are possible for price-based incentive schemes that do not exceed specific limits, or have "no or at most minimal trade-distorting effects on production" and do "not have the effect of providing price support to farmers"[180]. And, to the extent that any price incentive scheme for recycling P could be part of a "clearly defined" governmental environmental programme, the amount paid to farmers must be "limited to the extra costs or loss of income involved in complying with the government programme"[181]. However, the risk of an adverse WTO ruling remains.

Cap-and-trade systems for P contained in manure (as for CO_2 emissions) have also been suggested for improving P management[21] and have even been implemented in the Netherlands[182]. However, this approach can be problematic because watersheds and waterbodies are affected by local pollution. Therefore, unlike CO_2 emissions, choosing where to cap and trade becomes crucial, especially in light of the need for improved manure management and transportation logistics. Regulations should support safe, new technologies and recovered P products in agriculture and industry, despite inter-sectoral legal difficulties. For example, the EU's Carbon Border Adjustment Mechanism (CBAM) attempts to address regulatory issues regarding CO_2 emissions on imported goods, but questions remain about the feasibility of CBAM's implementation and compatibility with WTO trade rules. Alternatively, subsidy reforms, such as reducing mineral fertilizer subsidies (as in China[183]) or transforming agricultural subsidies (as in the EU and USA) can encourage the use of recovered fertilizers and sustainable practices, shifting subsidies toward improved P management, provided that challenges around subsidy design to ensure compatibility with WTO trade rules can be overcome[178,184].

Large, centralized facilities could take advantage of economies of scale to make P recycling economically viable in areas that are highly urbanized or have dense livestock production[185]. Such facilities optimize labour, energy and raw material use, reducing operational costs and maximizing output efficiency. However, centralization comes with its own set of financial and operational risks, such as supply chain interruptions and regulatory compliance issues, as well as limited ability to adapt to local market conditions[185]. By contrast, decentralized, small-scale solutions such as on-farm urine sterilization or manure processing can be more suitable in rural or low-income settings where nutrient demand and supply are more locally balanced, and transport distances are shorter. This contrasting suitability is due to the high capital investment required for constructing and maintaining large-scale facilities, which can be a notable financial burden that affects the decision-making of implementing P recycling.

[H2] Transdisciplinarity in phosphorus recycling

Interdisciplinary frameworks and decision support tools are vital for developing comprehensive P sustainability strategies. The EU-centred 5R phosphorus stewardship framework offers a broad model that includes realigning P inputs, reducing losses, recycling secondary resources, recovering P from waste, and redefining food systems through demand shifts[186]. Technologies and practices must achieve both technical and societal acceptance, addressing both community impacts and agronomic needs[187]. Similarly, the 'net-zero phsophorus cities' framework emphasizes the role of urban areas in creating circular P economies by capturing wastewater P[153]. These frameworks could be improved with better empirical data[188–190] and holistic integration of disciplinary perspectives.

We call for a transdisciplinary approach that incorporates non-academic stakeholders to ensure full co-production of strategies (Box 1). Collaboration must transcend individual interests and focus on shared goals, such as reducing runoff, improving nutrient-use efficiency and promoting recycling[191]. Transdisciplinarity enables a holistic understanding of the P cycle by integrating insights from agriculture, waste, environment, economics and policy sectors. Although transdisciplinarity faces challenges such as securing long-term funding, time-consuming coordination and communication among diverse stakeholders[57,148], it fosters innovative solutions for P recycling and pollution reduction, ensuring that strategies are practical and sustainable. Transdisciplinary efforts must inform policies that address P management complexities from local to global levels[21,22].

Phosphorus-focused organizations, such as the Global Phosphorus Research Initiative, the European Sustainable Phosphorus Platform, the US Sustainable Phosphorus Alliance, the Australian Sustainable Phosphorus Futures and the Phosphorus Industry Development Organisation of Japan), have a key role in coordinating efforts by connecting stakeholders and facilitating P-recovery strategies[192]. These agencies should serve as 'mediators' in stakeholder relationships. In regions where they do not exist, efforts should focus on engaging stakeholders beyond sectoral boundaries, thus paving the way for technological scaling, supportive policies and regulatory frameworks[148] while ensuring a transition to circular P economies[58].

Transdisciplinary research must promote broad and inclusive participation, ensuring that diverse perspectives are represented in decision-making. This approach supports fair processes and fosters more widely acceptable solutions. The potential of the transdisciplinary approach is exemplified by the UK Phosphorus Transformation Strategy[193] that involves extensive stakeholder engagement and has already produced a credible roadmap for multi-sectoral action across the P value chain, which can be broadened to other regions (Fig. 4). Future efforts should foster knowledge exchange to identify stakeholder interests and challenges, create local pathways, assign responsibilities and develop realistic timelines for P recycling targets[148].

[H1] Summary and future perspectives

Recycling is an important step towards P circularity, but global adoption remains limited owing to economic, technical, societal, regulatory and political barriers. The technical complexity of P recycling technologies[89], small scale of operations and high production costs make recycled fertilizers considerably more expensive than conventional, rock-derived fertilizers, as shown in Switzerland[137]. Recycled P products are also more chemically and physically complex, complicating attempts to understand their agricultural efficiency, impacts on human health and long-term environmental safety[129]. Limited production, logistical hurdles in transport and utilization, and uncertain financial returns further discourage adoption, as demonstrated in Sweden[133]. Meanwhile, narrow, disciplinary stakeholder focus and diverse socioeconomic and environmental realities across regions hinder collaboration and stifle global progress in P recycling[148].

Despite growing awareness of the importance of P recycling, challenges in accurately determining global P flows and uncertainties around the agronomic efficiency, safety, and environmental impacts of recycled P fertilizers continue to hamper progress. In addition, diverse agricultural systems and regulatory frameworks further complicate the development of coherent global strategies. This fragmentation extends across the whole P system: researchers, farmers, policymakers, environmental agencies and consumers each prioritise different goals, creating misalignments that undermine coordinated action. Bridging these gaps requires improved communication, transdisciplinary collaboration, and context-specific solutions that balance technical, societal and environmental needs.

Transforming P management requires a holistic approach in which stakeholders prioritize the shared objective of tackling the wicked problem of P circularity. Key goals include minimising waste generation, reducing P runoff, enhancing nutrient-use efficiency and promoting P recycling efforts. Breaking down barriers across sectors is essential: improved communication, transdisciplinary research and diverse perspectives can lay the foundation for an integrated approach to P circularity. Inclusive policies that address the needs of all stakeholders can drive collective action. Strategic research developments and actionable priorities will support progress over the next decade (Table 2).

Supporting these efforts requires a concerted push, through targeted incentives for sustainable P use, coherent regulation at local, regional and international scales, investments in innovation and research and the creation of inclusive platforms that facilitate transparent dialogue across sectors. Ultimately, the transition to circular P systems will depend on the ability of stakeholders to break down disciplinary, institutional and geographic silos, fostering collaboration that bridges science, policy and practice. Only then can resilient, sustainable P management strategies be built that are capable of reshaping the current linear supply chains into circular systems for the future.

References

1. Chen, M. & Graedel, T. E. A half-century of global phosphorus flows, stocks, production, consumption, recycling, and environmental impacts. *Glob. Environ. Change* **36**, 139–152 (2016).

2. U.S. Geological Survey, 2024, Mineral commodity summaries 2024: U.S. Geological Survey, 212 p., https://doi.org/10.3133/mcs2024

3. Haldar, S. K. Mineral Exploration. in *Mineral Exploration* (Elsevier, 2018). doi:10.1016/b978-0-12-814022-2.00001-0.

4. Reetz, H. F. *F*ertilizers and Their Efficient Use. International Fertilizer industry Association, IFA, Paris (2016).

5. IFA. Phosphate Rock Resources & Reserves. https://www.fertilizer.org/wp-content/uploads/2023/04/2023_Argus_IFA_Phosphate_Rock_Resources_and_Reserves_Final.pdf (2023).

6. Brownlie, W. J., Sutton, M. A., Heal, K. V., Reay, D. S. & Spears, B. M. Our Phosphorus Future. 222–223 (2022) doi:10.13140/RG.2.2.17834.08645.

7. Chen, Y. & Chen, M. Evolution of the global phosphorus trade network: A production perspective on resilience. *J. Clean. Prod.* **405**, 136843 (2023).

8. Geissler, B., Hermann, L., Mew, M. C. & Steiner, G. Striving Toward a Circular Economy for Phosphorus: The Role of Phosphate Rock Mining. *Minerals* **8**, 395 (2018).

9. Scholz, R. W. & Wellmer, F. W. Losses and use efficiencies along the phosphorus cycle. Part 1: Dilemmata and losses in the mines and other nodes of the supply chain. *Resour. Conserv. Recycl.* **105**, 216–234 (2015).

10. Walsh, M., Schenk, G. & Schmidt, S. Realising the circular phosphorus economy delivers for sustainable development goals. *npj Sustain. Agric.* **1**, 1–15 (2023).

11. Liu, X., Zhang, Y., Cheng, M., Jiang, S. & Yuan, Z. Recycling phosphorus from waste in China: Recycling methods and their environmental and resource consequences. *Resour. Conserv. Recycl.* **188**, 106669 (2023).

12. Teodoro, D. L. da C., Rocha, S. M. da & Benicio, L. P. F. Toward Agricultural Resilience: Analyzing Brazil's National Fertilizer Plan. *Sci. Technol. Public Policy* **8**, 9–14 (2024).

13. Ministério da Indústria, C. E. e S. Plano Nacional de Fertilizantes 2050: Uma estratégia para os fertilizantes no Brasil. *Ministério da Gestão e da Inovação em Serviços Públicos* (MGI), Brasília, DF (2023).

14. Smol, M. The importance of sustainable phosphorus management in the circular economy (CE) model: the Polish case study. *J. Mater. Cycles Waste Manag.* **21**, 227–238 (2019).

15. Mayer, B. K. *et al.* Total Value of Phosphorus Recovery. *Environ. Sci. Technol.* **50**, 6606–6620 (2016).

16. Devault, M., Woolf, D. & Lehmann, J. Nutrient recycling potential of excreta for global crop and grassland production. *Nat Sustain* **8**, 99–111 (2025).

17. Egle, L., Rechberger, H., Krampe, J. & Zessner, M. Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. *Sci. Total Environ.* **571**, 522–542 (2016).

18. Jupp, A. R., Beijer, S., C. Narain, G., Schipper, W. & Chris Slootweg, J. Phosphorus recovery and recycling – closing the loop. *Chemical Society Reviews* **50**, 87–101 (2021).

19. Bernal, M. P. *et al.* Evaluation of manure management systems in Europe. Final report LIFE + MANEV (No. LIFE09 ENV/ES/000453). (2015).

20. European Commission. Treating urban waste water: new data shows improvement across Europe. (2021). https://environment.ec.europa.eu/news/treating-urban-waste-water-new-data-shows-improvement-across-europe-2021-11-19_en#:~:text=On%20the%20occasion%20of%20the,in%20line%20with%20EU%20standards

21. Garske, B. & Ekardt, F. Economic policy instruments for sustainable phosphorus management: taking into account climate and biodiversity targets. *Environ. Sci. Eur.* **33**, (2021).

22. Kalpakchiev, T., Fraundorfer, M., Jacobs, B., Martin-Ortega, J. & Cordell, D. Transforming the European Union's phosphorus governance through holistic and intersectoral framings. *Front. Sustain. Resour. Manag.* **2**, (2023).

23. Zhu, F., Cakmak, E. K. & Cetecioglu, Z. Phosphorus recovery for circular Economy: Application potential of feasible resources and engineering processes in Europe. *Chem. Eng. J.* **454**, 140153 (2023).

24. Cordell, D. & White, S. Life's Bottleneck: Sustaining the World's Phosphorus for a Food Secure Future. *Annu. Rev. Environ. Resour.* **39**, 161–188 (2014).

25. Hosseinian, A., Pettersson, A., Ylä-Mella, J. & Pongrácz, E. Phosphorus recovery methods from secondary resources, assessment of overall benefits and barriers with focus on the Nordic countries. *J. Mater. Cycles Waste Manag.* **25**, 3104–3116 (2023).

26. Aarikka-Stenroos, L., Kokko, M. & Pohls, E. L. Catalyzing the circular economy of critical resources in a national system: Case study on drivers, barriers, and actors in nutrient recycling. *J. Clean. Prod.* **397**, (2023).

27. Lou, H. *et al.* Quantitative evaluation of legacy phosphorus and its spatial distribution. *J. Environ. Manage.* **211**, 296–305 (2018).

28. Solangi, F. *et al.* The Global Dilemma of Soil Legacy Phosphorus and Its Improvement Strategies under Recent Changes in Agro-Ecosystem Sustainability. *ACS Omega* **8**, 23271–23282 (2023).

29. Pavinato, P. S. *et al.* Revealing soil legacy phosphorus to promote sustainable agriculture in Brazil. *Sci. Rep.* **10**, (2020).

30. Li, B. *et al.* Network evolution and risk assessment of the global phosphorus trade. *Sci. Total Environ.* **860**, (2023).

31. Powers, S. M. *et al.* Global Opportunities to Increase Agricultural Independence Through Phosphorus Recycling. *Earth's Future* **7**, 370–383 (2019).

32. Cordell, D. & Neset, T. S. S. Phosphorus vulnerability: A qualitative framework for assessing the vulnerability of national and regional food systems to the multi-dimensional stressors of phosphorus scarcity. *Glob. Environ. Change.* **24**, 108–122 (2014).

33. Nanda, M., Cordell, D. & Kansal, A. Assessing national vulnerability to phosphorus scarcity to build food system resilience: The case of India. *J. Environ. Manage.* **240**, 511–517 (2019).

34. Pistilli, M. Top 10 Phosphate Countries by Production (Updated 2024) | INN. https://investingnews.com/daily/resource-investing/agriculture-investing/phosphate-investing/top-phosphate-countries-by-production/ (2024).

35. Bonini, C. & Wesenbeeck, C. F. A. The Economics of Phosphorus: Does its Price Reect its Attributes? An economic and geopolitical analysis of the market for phosphate rock. (2023) doi:10.21203/rs.3.rs-2519554/v1.

36. Mew, M. C. Phosphate rock costs, prices and resources interaction. *Sci. Total Environ.* **542**, 1008–1012 (2016).

37. Cordell, D. & White, S. Peak Phosphorus: Clarifying the Key Issues of a Vigorous Debate about Long-Term Phosphorus Security. *Sustainability* **3**, 2027–2049 (2011).

38. Cordell, D., Drangert, J.-O. & White, S. The story of phosphorus: Global food security and food for thought. *Glob. Environ. Change.* **19**, 292–305 (2009).

39. Moosavi, J., Fathollahi-Fard, A. M. & Dulebenets, M. A. Supply chain disruption during the COVID-19 pandemic: Recognizing potential disruption management strategies. *Int. J. Disaster Risk Reduct.* **75**, 102983 (2022).

40. Kee, J., Cardell, L. & Zereyesus, Y. A. USDA ERS - Global Fertilizer Market Challenged by Russia's Invasion of Ukraine. https://www.ers.usda.gov/amber-waves/2023/september/global-fertilizer-market-challenged-by-russia-s-invasion-of-ukraine/ (2023).

41. Chow, E. & Patton, D. China issues phosphate quotas to rein in fertiliser exports - analysts. *Reuters* (2022). https://www.reuters.com/article/markets/currencies/china-issues-phosphate-quotas-to-rein-in-fertiliser-exports-analysts-idUSKBN2OQ0KX/

42. White, E. US, Canadian farmers face soaring fertilizer prices amid Trump trade war. *Reuters* (2025). https://www.reuters.com/markets/commodities/us-canadian-farmers-face-soaring-fertilizer-prices-amid-trump-trade-war-2025-03-07/

43. IFPRI. Global fertilizer trade 2021-2023: What happened after war-related price spikes. *IFPRI* https://www.ifpri.org/blog/global-fertilizer-trade-2021-2023-what-happened-after-war-related-price-spikes/ (2024).

44. de Ridder, M., de Jong, S., Polchar, J. & Lingemann, S. Risks and Opportunities in the Global Phosphate Rock Market. Robust Strategies in Times of Uncertainty. *HCSS* https://hcss.nl/report/risks-and-opportunities-in-the-global-phosphate-rock-market-robust-strategies-in-times-of-uncertainty/ (2012).

45. Brunner, P. H. Substance Flow Analysis as a Decision Support Tool for Phosphorus Management. *J. Ind. Ecol.* **14**, 870–873 (2010).

46. Brownlie, W. J. *et al.* Phosphorus price spikes: A wake-up call for phosphorus resilience. *Front. Sustain. Food Syst.* **7**, (2023).

47. Dijk, K. C. van, Lesschen, J. P. & Oenema, O. Phosphorus flows and balances of the European Union Member States. *Sci. Total Environ*. **542**, 1078–1093 (2016).

48. Lun, F. *et al.* Global and regional phosphorus budgets in agricultural systems and their implications for phosphorus-use efficiency. *Earth Syst. Sci. Data* **10**, 1–18 (2018).

49. Vanlauwe, B. *et al.* In: Fertilizer and Soil Health in Africa: The Role of Fertilizer in Building Soil Health to Sustain Farming and Address Climate Change. International Fertilizer Development Center - IFDC (2023).

50. Sabo, R. D. *et al.* Phosphorus Inventory for the Conterminous United States (2002–2012). *J. Geophys. Res. Biogeosci.* **126**, e2020JG005684 (2021).

51. Liu, W. *et al.* Global Phosphorus Losses from Croplands under Future Precipitation Scenarios. *Environ. Sci. Technol.* **54**, 14761–14771 (2020).

52. Wang, R., Cai, C., Zhang, J., Sun, S. & Zhang, H. Study on phosphorus loss and influencing factors in the water source area. *Int. Soil Water Conserv. Res.* **10**, 324–334 (2022).

53. Mekonnen, M. M. & Hoekstra, A. Y. Global Anthropogenic Phosphorus Loads to Freshwater and Associated Grey Water Footprints and Water Pollution Levels: A High-Resolution Global Study. *Water Resour. Res.* **54**, 345–358 (2018).

54. European Union. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Parliament* **L327**, (2000).

55. Tu, L. *et al.* Anthropogenic modification of phosphorus sequestration in lake sediments during the Holocene: A global perspective. *Glob. Planet. Change* **229**, (2023).

56. Bilal, E. *et al.* Phosphogypsum circular economy considerations: A critical review from more than 65 storage sites worldwide. *J. Clean. Prod.* **414**, 137561 (2023).

57. Jama-Rodzeńska, A., Białowiec, A., Koziel, J. A. & Sowiński, J. Waste to phosphorus: A transdisciplinary solution to P recovery from wastewater based on the TRIZ approach. *J. Environ. Manage.* **287**, 112235 (2021).

58. Carrillo, V., Castillo, R., Magrí, A., Holzapfel, E. & Vidal, G. Phosphorus recovery from domestic wastewater: A review of the institutional framework. *J. Environ. Manage.* **351**, 119812 (2024).

59. Girotto, F., Alibardi, L. & Cossu, R. Food waste generation and industrial uses: A review. *Waste Manag.* **45**, 32–41 (2015).

60. Yu, Y. hui, Du, C. ming, Zhang, Y. tang & Yuan, R. yuan. Phosphorus recovery from phosphate tailings through a two-stage leaching-precipitation process: Toward the harmless and reduction treatment of P-bearing wastes. *Environ. Res.* **248**, 118328 (2024).

61. Xiao, Y. *et al.* Co-pyrolysis of sewage sludge and phosphate tailings: Synergistically enhancing heavy metal immobilization and phosphorus availability. *Waste Manag.* **181**, 44–56 (2024).

62. Spooren, J. *et al.* Near-zero-waste processing of low-grade, complex primary ores and secondary raw materials in Europe: technology development trends. *Resour. Conserv. Recycl.* **160**, 104919 (2020).

63. Singh, M. Treating waste phosphogypsum for cement and plaster manufacture. *Cem. Concr. Res.* **32**, 1033–1038 (2002).

64. Fuleihan, N. F. Phosphogypsum disposal - The pros & cons of wet versus dry stacking. in *Procedia Eng.* **46**, 195–205 (Elsevier Ltd, 2012).

65. Pliaka, M. & Gaidajis, G. Potential uses of phosphogypsum: A review. *J. Environ. Sci. Health A.* **57**, 746–763 (2022).

66. Panagos, P. *et al.* Improving the phosphorus budget of European agricultural soils. *Sci. Total Environ*. **853**, 158706 (2022).

67. Köninger, J. *et al.* Manure management and soil biodiversity: Towards more sustainable food systems in the EU. *Agric. Syst.* **194**, 103251 (2021).

68. Zhang, Q. *et al.* Comprehensive assessment of the utilization of manure in China's croplands based on national farmer survey data. *Sci. Data* **10**, 223 (2023).

69. Bai, Z. *et al.* Nitrogen, Phosphorus, and Potassium Flows through the Manure Management Chain in China. *Environ. Sci. Technol.* **50**, 13409–13418 (2016).

70. Hjorth, M. & Jørgensen, B. U. Polymer flocculation mechanism in animal slurry established by charge neutralization. *Water Res.* **46**, 1045–1051 (2012).

71. Hjorth, M., Christensen, K. V., Christensen, M. L. & Sommer, S. G. Solid—liquid separation of animal slurry in theory and practice. A review. *Agron. Sustain. Dev.* **30**, 153–180 (2010).

72. Möller, K. & Müller, T. Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. *Eng. Life Sci.* **12**, 242–257 (2012).

73. Kabeyi, M. J. B. & Olanrewaju, O. A. Biogas Production and Applications in the Sustainable Energy Transition. *J. Energy* **2022**, 8750221 (2022).

74. Haldar, D. *et al.* Understanding the management of household food waste and its engineering for sustainable valorization- A state-of-the-art review. *Bioresour. Technol.* **358**, 127390 (2022).

75. Garcia-Garcia, G., Woolley, E. & Rahimifard, S. Optimising Industrial Food Waste Management. *Procedia Manuf.* **8**, 432–439 (2017).

76. Otles, S., Despoudi, S., Bucatariu, C. & Kartal, C. Food waste management, valorization, and sustainability in the food industry. *Food Waste Recover.* 3–23. (2015).

77. Ruffatto, K., Shurson, G. C., Muenich, R. L. & Cusick, R. D. Modeling National Embedded Phosphorus Flows of Corn Ethanol Distillers' Grains to Elucidate Nutrient Reduction Opportunities. *Environ. Sci. Technol.* **57**, 14429–14441 (2023).

78. Chia, D. *et al.* A systematic review of country-specific drivers and barriers to household food waste reduction and prevention. *Waste Manag. Res.* **42**, 459–475 (2024).

79. Schanes, K., Dobernig, K. & Gözet, B. Food waste matters - A systematic review of household food waste practices and their policy implications. *J. Clean. Prod.* **182**, 978–991 (2018).

80. Arcas-Pilz, V., Gabarrell, X., Orsini, F. & Villalba, G. Literature review on the potential of urban waste for the fertilization of urban agriculture: A closer look at the metropolitan area of Barcelona. *Sci. Total Environ.* **905**, 167193 (2023).

81. Mokjatturas, S., Chinwetkitvanich, S., Patthanaissaranukool, W., Polprasert, C. & Polprasert, S. Phosphorus mass flows and economic benefits of food waste management: the case study of selected retail and wholesale fresh markets in Thailand. *Clean Techn. Environ. Policy* **27**, 219–233 (2025).

82. Jones, E. R., Vliet, M. T. H. V., Qadir, M. & Bierkens, M. F. P. Country-level and gridded estimates of wastewater production, collection, treatment and reuse. *Earth Syst. Sci. Data* **13**, 237–254 (2021).

83. Kok, D. J. D. *et al.* Global phosphorus recovery from wastewater for agricultural reuse. *Hydrol. Earth Syst. Sci.* **22**, 5781–5799 (2018).

84. Diaz, R. *et al.* Enhanced Bio-P removal: Past, present, and future – A comprehensive review. *Chemosphere* **309**, 136518 (2022).

85. Korving, L., Loosdrecht, M. V. & Wilfert, P. Effect of iron on phosphate recovery from sewage sludge. in *Phosphorus Recovery and Recycling* 303–326 (Springer Singapore, 2018). 10.1007/978-981-10-8031-9_21.

86. Witek-Krowiak, A. *et al.* Phosphorus recovery from wastewater and bio-based waste: an overview. *Bioengineered* **13**, 13474–13506 (2022).

87. Denmark. Danmark uden affald - Genanvend mere - forbrænd mindre (2013) https://regeringen.dk/media/ke3hq3tx/danmark_uden_affald__genanvend_mere__forbraend_mindre.pdf

88. European Sustainable Phosphorus Platform (ESPP). Catalogue of Nutrient Recovery Technologies. *https://phosphorusplatform.eu/activities/p-recovery-technology-inventory* (2023).

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

90. Wijdeveld, W. K. *et al.* Pilot-scale magnetic recovery of vivianite from digested sewage sludge. *Water Res.* **212**, 118131 (2022).

91. Quist-Jensen, C. A. *et al.* Acidification and recovery of phosphorus from digested and non-digested sludge. *Water Res.* **146**, 307–317 (2018).

92. Amann, A. *et al.* Environmental impacts of phosphorus recovery from municipal wastewater. *Resour. Conserv. Recycl.* **130**, 127–139 (2018).

93. Zhu, Y. *et al.* Thermal treatment of sewage sludge: A comparative review of the conversion principle, recovery methods and bioavailability-predicting of phosphorus. *Chemosphere* **291**, 133053 (2022).

94. Kiani, M. *et al.* Recycling eutrophic lake sediments into grass production: A four-year field experiment on agronomical and environmental implications. *Sci. Total Environ.* **870**, 161881 (2023).

95. Gatiboni, L. C. *et al.* Plant uptake of legacy phosphorus from soils without P fertilization. *Nutr. Cycl. Agroecosyst.* **119**, 139–151 (2021).

96. Sattari, S. Z., Bouwman, A. F., Giller, K. E. & Ittersum, M. K. V. Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 6348–6353 (2012).

97. Demay, J., Ringeval, B., Pellerin, S. & Nesme, T. Half of global agricultural soil phosphorus fertility derived from anthropogenic sources. *Nat. Geosci.* **16**, 69–74 (2023).

98. Zhang, J. *et al.* Spatiotemporal dynamics of soil phosphorus and crop uptake in global cropland during the 20th century. *Biogeosciences* **14**, 2055–2068 (2017).

99. Hallama, M., Pekrun, C., Lambers, H. & Kandeler, E. Hidden miners – the roles of cover crops and soil microorganisms in phosphorus cycling through agroecosystems. *Plant Soil* **434**, 7–45 (2019).

100. Lambers, H., Shane, M. W., Cramer, M. D., Pearse, S. J. & Veneklaas, E. J. Root structure and functioning for efficient acquisition of phosphorus: Matching morphological and physiological traits. *Ann. Bot.* **98**, 693–713 (2006).

101. Zhu, Y., Yan, F., Zörb, C. & Schubert, S. A link between citrate and proton release by proteoid roots of white lupin (Lupinus albus L.) grown under phosphorus-deficient conditions? *Plant Cell Physiol.* **46**, 892–901 (2005).

102. Richardson, A. E. *et al.* Plant and microbial strategies to improve the phosphorus efficiency of agriculture. *Plant Soil* **349**, 121–156 (2011).

103. Ojeda-Rivera, J. O., Alejo-Jacuinde, G., Nájera-González, H.-R. & López-Arredondo, D. Prospects of genetics and breeding for low-phosphate tolerance: an integrated approach from soil to cell. *Theor. Appl. Genet.* **135**, 4125–4150 (2022).

104. Jha, U. C. *et al.* Breeding and genomics approaches for improving phosphorus-use efficiency in grain legumes. *Environ. Exp. Bot.* **205**, 105120 (2023).

105. Oburger, E., Jones, D. L. & Wenzel, W. W. Phosphorus saturation and pH differentially regulate the efficiency of organic acid anion-mediated P solubilization mechanisms in soil. *Plant Soil* **341**, 363–382 (2011).

106. Carver, R. E. *et al.* Cover crop and phosphorus fertilizer management impacts on surface water quality from a no-till corn-soybean rotation. *J. Environ. Manage.* **301**, 113818 (2022).

107. Zhu, J., Li, M. & Whelan, M. Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: A review. *Sci. Total Environ.* **612**, 522–537 (2018).

108. Ogunsanya, H. Y. *et al.* Belgian endive-derived biostimulants promote shoot and root growth in vitro. *Sci. Rep.* **12**, 8792 (2022).

109. Kirol, A. P. *et al.* Linking Sediment and Water Column Phosphorus Dynamics to Oxygen, Temperature, and Aeration in Shallow Eutrophic Lakes. *Water Resour. Res.* **60**, e2023WR034813 (2024).

110. Simoni, G. *et al.* Flocculating and dewatering of lake sediment: An in-situ pilot study comparing synthetic polymers and biopolymers for restoring lake water quality and reusing phosphorus. *Sci. Total Environ.* **913**, 169597 (2024).

111. Hollas, C. E. *et al.* Second-Generation Phosphorus: Recovery from Wastes towards the Sustainability of Production Chains. *Sustainability* **13**, 5919 (2021).

112. Joint Research Centre (European Commission) *et al.* Screening Risk Assessment of Organic Pollutants and Environmental Impacts from Sewage Sludge Management: Study to Support Policy Development on the Sewage Sludge Directive (86/278/EEC). *Publications Office of the European Union* (2022).

113. Directorate-General for Environment (European Commission) *et al.* Support to the Evaluation of the Sewage Sludge Directive: Final Study Report. *Publications Office of the European Union* (2022).

114. Sichler, T. C. *et al.* Determination of the phosphorus content in sewage sludge: comparison of different aqua regia digestion methods and ICP-OES, ICP-MS, and photometric determination. *Environ. Sci. Eur.* **34**, 99 (2022).

115. Duboc, O., Hernandez-Mora, A., Wenzel, W. W. & Santner, J. Improving the prediction of fertilizer phosphorus availability to plants with simple, but non-standardized extraction techniques. *Sci. Total Environ.* **806**, 150486 (2022).

116. Hernandez-Mora, A. *et al.* Fertilization efficiency of thirty marketed and experimental recycled phosphorus fertilizers. *J. Clean. Prod.* **467**, 142957 (2024).

117. Smit, A. L., Van Middelkoop, J. C., Van Dijk, W. & Van Reuler, H. A substance flow analysis of phosphorus in the food production, processing and consumption system of the Netherlands. *Nutr. Cycl. Agroecosyst.* **103**, 1–13 (2015).

118. Talboys, P. J. *et al.* Struvite: a slow-release fertiliser for sustainable phosphorus management? *Plant Soil* **401**, 109–123 (2016).

119. Deinert, L., Ikoyi, I., Egeter, B., Forrestal, P. & Schmalenberger, A. Short-Term Impact of Recycling-Derived Fertilizers on Their P Supply for Perennial Ryegrass (Lolium perenne). *Plants* **12**, 2762 (2023).

120. Dox, K., Martin, T., Houot, S., Merckx, R. & Smolders, E. Superior residual fertiliser value in soil with phosphorus recycled from urine in layered double hydroxides. *Sci. Rep.* **12**, 8092 (2022).

121. Kratz, S., Vogel, C. & Adam, C. Agronomic performance of P recycling fertilizers and methods to predict it: a review. *Nutr. Cycl. Agroecosyst.* **115**, 1–39 (2019).

122. Buss, W., Assavavittayanon, K., Shepherd, J. G., Heal, K. V. & Sohi, S. Biochar Phosphorus Release Is Limited by High pH and Excess Calcium. *J. Environ. Qual.* **47**, 1298–1303 (2018).

123. Hertzberger, A. J., Cusick, R. D. & Margenot, A. J. A review and meta-analysis of the agricultural potential of struvite as a phosphorus fertilizer. *Soil Sci. Soc. Am. J.* **84**, 653–671 (2020).

124. Lam, K. L., Zlatanović, L. & Hoek, J. P. van der. Life cycle assessment of nutrient recycling from wastewater: A critical review. *Water Res.* **173**, 115519 (2020).

125. Harvey, F. & correspondent, F. H. E. Nearly 30,000 tonnes of sewage sludge containing human waste to enter UK. *The Guardian* (2020). https://www.theguardian.com/environment/2020/sep/02/sewage-sludge-containing-human-waste-uk

126. Flynn, K. C., Spiegal, S., Kleinman, P. J. A., Meinen, R. J. & Smith, D. R. Manureshed management to overcome longstanding nutrient imbalances in US agriculture. *Resour. Conserv. Recycl.* **188**, 106632 (2023).

127. Ghimire, S., Wang, J. & Fleck, J. R. Integrated crop-livestock systems for nitrogen management: A multi-scale spatial analysis. *Animals* **11**, 1–21 (2021).

128. Tonini, D., Saveyn, H. G. M. & Huygens, D. Environmental and health co-benefits for advanced phosphorus recovery. *Nat. Sustain.* **2**, 1051–1061(2019).

129. Lessmann, M., Kanellopoulos, A., Kros, J., Orsi, F. & Bakker, M. Maximizing agricultural reuse of recycled nutrients: A spatially explicit assessment of environmental consequences and costs. *J. Environ. Manage.* **332**, (2023).

130. Teenstra, E. *et al.* Global Assessment of Manure Management Policies and Practices. (2014).

131. Li, J. *et al.* Optimal manure utilization chain for distributed animal farms: Model development and a case study from Hangzhou, China. *Agric. Syst.* **187**, 102996 (2021).

132. Khodadadi, M., Masoumi, A., Sadeghi, M. & Moheb, A. Optimization of drying specification and protein losses of poultry litter during drying process using response surface methodology. *Therm. Sci. Eng. Prog.* **43**, 101958 (2023).

133. Akram, U., Quttineh, N. H., Wennergren, U., Tonderski, K. & Metson, G. S. Enhancing nutrient recycling from excreta to meet crop nutrient needs in Sweden – a spatial analysis. *Sci. Rep.* **9**, 10264 (2019).

134. Panday, D., Bhusal, N., Das, S. & Ghalehgolabbehbahani, A. Rooted in Nature: The Rise, Challenges, and Potential of Organic Farming and Fertilizers in Agroecosystems. *Sustainability* **16**, 1530 (2024).

135. Case, S. D. C., Oelofse, M., Hou, Y., Oenema, O. & Jensen, L. S. Farmer perceptions and use of organic waste products as fertilisers – A survey study of potential benefits and barriers. *Agric. Syst.* **151**, 84–95 (2017).

136. Grieger, K., Merck, A., Deviney, A. & Marshall, A. What are stakeholder views and needs for achieving phosphorus sustainability? *Environ. Syst. Decis.* **44**, 114–125 (2024).

137. Schlumberger, S. Phos4life am Standort Emmenspitz. (2023). https://zar-ch.ch/fileadmin/user_upload/Contentdokumente/Phos4Life2023/20230425_P4L_Emmenspitz_Aktueller_Statusbericht_April_2023.pdf

138. FOB Rotterdam. Phosphoric Acid Prices, News, Monitor, Analysis & Demand. https://www.chemanalyst.com/Pricing-data/phosphoric-acid-1162 (2024).

139. Uzkurt Kaljunen, J., Al-Juboori, R. A., Khunjar, W., Mikola, A. & Wells, G. Phosphorus recovery alternatives for sludge from chemical phosphorus removal processes – Technology comparison and system limitations. *Sustain. Mater. Technol.* **34**, e00514 (2022).

140. Maaß, O., Grundmann, P. & Polach, C. V. B. U. Added-value from innovative value chains by establishing nutrient cycles via struvite. *Resour. Conserv. Recycl.* **87**, 126–136 (2014).

141. Mudragada, R. *et al.* Phosphorous removal during sludge dewatering to prevent struvite formation in sludge digesters by full scale evaluation. *J. Water Process Eng.* **2**, 37–42 (2014).

142. Siciliano, A., Limonti, C., Curcio, G. M. & Molinari, R. Advances in struvite precipitation technologies for nutrients removal and recovery from aqueous waste and wastewater. *Sustainability* **12**, 7538 (2020).

143. Rice, B. & Vos, R. Who's afraid of high fertilizer prices? | Africa South of the Sahara. https://ssa.foodsecurityportal.org/node/2733 (2024).

144. Krüger, O. & Adam, C. Phosphorus in recycling fertilizers - analytical challenges. *Environ. Res.* **155**, 353–358 (2017).

145. van der Kooij, S. *et al.* Phosphorus recovered from human excreta: A socio-ecological-technical approach to phosphorus recycling. *Resour. Conserv. Recycl.* **157**, 104744 (2020).

146. Marks, J., Martin, B. & Zadoroznyj, M. How Australians order acceptance of recycled water. *J. Sociol.* (2008) doi:10.1177/1440783307085844.

147. Ricart, S., Rico, A. M. & Ribas, A. Risk-Yuck Factor Nexus in Reclaimed Wastewater for Irrigation: Comparing Farmers' Attitudes and Public Perception. *Water* **11**, 187 (2019).

148. Martin-Ortega, J. *et al.* Are stakeholders ready to transform phosphorus use in food systems? A transdisciplinary study in a livestock intensive system. *Environ. Sci. Policy* **131**, 177–187 (2022).

149. Zhang, X. *et al.* Quantifying Nutrient Budgets for Sustainable Nutrient Management. *Glob. Biogeochem. Cycles* **34**, e2018GB006060 (2020).

150. Tyllianakis, E. *et al.* A window into land managers' preferences for new forms of agri-environmental schemes: Evidence from a post-Brexit analysis. *Land Use Policy* **129**, 106627 (2023).

151. Cardwell, M. Results-based agri-environmental scheme design: Legal implications. *Environ. Law Rev.* **25**, 260–288 (2023).

152. Brownlie, W. J. *et al.* Global actions for a sustainable phosphorus future. *Nat. Food* **2**, 71–74 (2021).

153. Metson, G. S., Brownlie, W. J. & Spears, B. M. Towards net-zero phosphorus cities. *npj Urban Sustain.* **2**, 1–9 (2022).

154. AbfKlärV. Verordnung über die Verwertung von Klärschlamm, Klärschlammgemisch und Klärschlammkompost (Klärschlammverordnung-AbfKlärV). (2017).

155. Sustainability, F. M. & Tourism. FEDERAL WASTE MANAGEMENT PLAN 2017 (PART 1). 209 (2017). https://www.bmluk.gv.at/dam/jcr:40f2e12e-479a-42ea-bd29-88333109f2c1/Federal_Waste_Management_Plan_2017_Part_2.pdf

156. The Swiss Federal Council. Ordinance on the Avoidance and the Disposal of Waste (Waste Ordinance, ADWO). (2015).

157. Sichler, T. C., Adam, C., Montag, D. & Barjenbruch, M. Future nutrient recovery from sewage sludge regarding three different scenarios - German case study. *J. Clean. Prod.* **333**, 130130 (2022).

158. Regulation (EU). PDF.pdf. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2019:170:FULL (2019).

159. Sakudo, A., Anraku, D. & Itarashiki, T. Inactivation of Prions by Low-Temperature Sterilization Technology Using Vaporized Gas Derived from a Hydrogen Peroxide–Peracetic Acid Mixture. *Pathogens* **10**, 24 (2020).

160. Hazards (BIOHAZ), E. P. on B. *et al.* Effect of incineration, co-incineration and combustion on TSE hazards in category 1 animal by-products. *EFSA J.* **23**, e9435 (2025).

161. European Sustainable Phosphorus Platform. Summary of ESPP webinar on Category 1 Animal By-Product Ash safety and prions. https://www.phosphorusplatform.eu/images/Regulatory%20activities/Summary%20ESPP%20ABP%20webinar%2022_5_23.pdf (2023).

162. Garske, B., Stubenrauch, J. & Ekardt, F. Sustainable phosphorus management in European agricultural and environmental law. *Rev. Eur. Comp. Int. Environ. Law* **29**, 107–117 (2020).

163. European Union. Urban Wastewater Treatment Directive 91/271/EEC. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:1991:135:FULL (1991).

164. Asai, M., Langer, V. & Frederiksen, P. Responding to environmental regulations through collaborative arrangements: Social aspects of manure partnerships in Denmark. *Livest. Sci.* **167**, 370–380 (2014).

165. European Union. EU Nitrates Directive 91/676EC. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31991L0676 (1991).

166. Steinfurth, K. *et al.* Thresholds of target phosphorus fertility classes in European fertilizer recommendations in relation to critical soil test phosphorus values derived from the analysis of 55 European long-term field experiments. *Agric. Ecosyst. Environ.* **332**, 107926 (2022).

167. Deviney, A., Grieger, K., Merck, A., Classen, J. & Marshall, A. M. Phosphorus sustainability through coordinated stakeholder engagement: a perspective. *Environ. Syst. Decis.* **43**, 371–378 (2023).

168. Pätzold, S., Leenen, M. & Heggemann, T. W. Proximal Mobile Gamma Spectrometry as Tool for Precision Farming and Field Experimentation. *Soil Syst.* **4**, 31 (2020).

169. Boer, M. A. de, Romeo-Hall, A. G., Rooimans, T. M. & Slootweg, J. C. An assessment of the drivers and barriers for the deployment of urban phosphorus recovery technologies: A case study of the Netherlands. *Sustainability* **10**, 1790 (2018).

170. Metson, G. S., Bennett, E. M. & Elser, J. J. The role of diet in phosphorus demand. *Environ. Res. Lett.* **7**, 044043 (2012).

171. Davidson, T. A. *et al.* Temporary stratification promotes large greenhouse gas emissions in a shallow eutrophic lake. *Biogeosciences* **21**, 93–107 (2024).

172. Sohoulande, C. D. D. *et al.* Evaluation of phosphorus runoff from sandy soils under conservation tillage with surface broadcasted recovered phosphates. *J. Environ. Manage.* **328**, 117005 (2023).

173. Withers, P. J. A., Sylvester-Bradley, R., Jones, D. L., Healey, J. R. & Talboys, P. J. Feed the Crop Not the Soil: Rethinking Phosphorus Management in the Food Chain. *Environ. Sci. Technol.* **48**, 6523–6530 (2014).

174. Lautrou, M., Cappelaere, L. & Létourneau Montminy, M.-P. Phosphorus and nitrogen nutrition in swine production. *Anim. Front.* **12**, 23–29 (2022).

175. Sajjad, M. *et al.* Methods for the removal and recovery of nitrogen and phosphorus nutrients from animal waste: A critical review. *Ecol. Front.* **44**, 2–14 (2024).

176. Lorick, D., Macura, B., Ahlström, M., Grimvall, A. & Harder, R. Effectiveness of struvite precipitation and ammonia stripping for recovery of phosphorus and nitrogen from anaerobic digestate: a systematic review. *Environ. Evid.* **9**, 27 (2020).

177. Schott, C. *et al.* Enabling efficient phosphorus recovery from cow manure: Liberation of phosphorus through acidification and recovery of phosphorus as calcium phosphate granules. *Chem. Eng. J.* **460**, 141695 (2023).

178. Hukari, S., Hermann, L. & Nättorp, A. From wastewater to fertilisers - Technical overview and critical review of European legislation governing phosphorus recycling. *Sci. Total Environ.* **542**, (2016).

179. Rolfe, J. & Windle, J. Using auction mechanisms to reveal costs for water quality improvements in Great Barrier Reef catchments in Australia. *Agric. Water Manag.* **98**, 493–501 (2011).

180. World Trade Organization. The WTO Agreements: Agreement on Agriculture, Annex 2:1. https://www.wto.org/english/docs_e/legal_e/ag_e.htm#ann2 (2022).

181. Smith, F. Mind the gap: 'Greening' direct payments and the World Trade Organization. in *Research Handbook on EU Agriculture Law* (eds. McMahon, J. A. & Cardwell, M. N.) (Edward Elgar Publishing, 2015). doi:10.4337/9781781954621.00031.

182. European Commission. State aid: Dutch phosphate rights trading system approved. *European Commission - European Commission* https://ec.europa.eu/commission/presscorner/detail/en/ip_17_5362 (2017).

183. Wu, Z., Feng, X., Zhang, Y. & Fan, S. Repositioning fertilizer manufacturing subsidies for improving food security and reducing greenhouse gas emissions in China. *J. Integr. Agric.* **23**, 430–443 (2024).

184. Heyl, K., Ekardt, F., Sund, L. & Roos, P. Potentials and Limitations of Subsidies in Sustainability Governance: The Example of Agriculture. *Sustainability* **14**, 15859 (2022).

185. Bagheri, M., Gómez-Sanabria, A. & Höglund-Isaksson, L. Economic feasibility and direct greenhouse gas emissions from different phosphorus recovery methods in Swedish wastewater treatment plants. *Sustain. Prod. Consum.* **49**, 462–473 (2024).

186. Withers, P. J. A. *et al.* Stewardship to tackle global phosphorus inefficiency: The case of Europe. *Ambio* **44**, 193–206 (2015).

187. Martin-Ortega, J. We cannot address global water challenges without social sciences. *Nat. Water* **1**, 2–3 (2023).

188. Leahey, E., Beckman, C. M. & Stanko, T. L. Prominent but Less Productive: The Impact of Interdisciplinarity on Scientists' Research*. *Adm. Sci. Q.* **62**, 105–139 (2017).

189. Liu, L., Jones, B. F., Uzzi, B. & Wang, D. Data, measurement and empirical methods in the science of science. *Nat. Hum. Behav.* **7**, 1046–1058 (2023).

190. Daniel, K. L., McConnell, M., Schuchardt, A. & Peffer, M. E. Challenges facing interdisciplinary researchers: Findings from a professional development workshop. *PLoS One* **17**, e0267234 (2022).

191. Martin-Ortega, J. *et al.* Are stakeholders ready to transform phosphorus use in food systems? A transdisciplinary study in a livestock intensive system. *Environ. Sci. Policy* **131**, 177–187 (2022).

192. Lyon, C. *et al.* Five pillars for stakeholder analyses in sustainability transformations: The global case of phosphorus. *Environ. Sci. Policy* **107**, 80–89 (2020).

193. Cordell, D. *et al.* UK Phosphorus Transformation Strategy: Towards a circular UK food system. 1–36 (2022). https://zenodo.org/records/7404622

194. Fang, L. *et al.* Feasibility of wet-extraction of phosphorus from incinerated sewage sludge ash (ISSA) for phosphate fertilizer production: A critical review. *Crit. Rev. Environ. Sci. Technol.* **51**, 939-971 (2021).

195. Suboticki, I. Transdisciplinarity: Breaking down disciplinary and academic barriers. *Cambridge: SSH CENTRE* (2023).

196. Rigolot, C. Transdisciplinarity as a discipline and a way of being: complementarities and creative tensions. *Humanit. Soc. Sci. Commun.* **7**, 100 (2020).

Acknowledgements

The authors thank David Stuligross for his expert copy editing. His sharp eye and thoughtful revisions greatly improved the clarity and readability of this manuscript. The RecaP project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 956454.

Competing interests

The authors declare no competing interests.

Disclaimer

The results expressed in this article are those of the authors only and do not necessarily reflect those of the European Union. The European Union cannot be held responsible for them.

Author contributions

H.R.R. and J.S.-G. contributed with project administration, conceptualization, visualization, data curation, and writing of the original draft. H.L.M. contributed with investigation, visualization, writing, review and editing. T.K., J.K, Y.Z., R.M.V. and S.M. contributed with investigation, writing, review and editing. A.J.G.-E. contributed with investigation. L.K., P.W. and T.P contributed with conceptualization, supervision, investigation, validation, writing, review and editing. J.M.-O., D.S.M.-S., M.v.L., D.C., J.S., H.L., L.H., M.S., M.L.C., F.v.d.B., S.K.J. and F.S. contributed with investigation, validation, writing, review and editing. N.S.R contributed with investigation, validation, visualization, writing, review and editing. K.R. contributed with project administration, conceptualization, supervision, investigation, validation, writing, review and editing.

Peer review information

Nature Reviews Earth & Environment thanks [Referee#1 name], [Referee#2 name] and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Display items

Table 1. Major secondary phosphorus resources and recycling techniques and challenges

Secondary P waste stream or legacy P stock	Global amount generated	Current fate	Potential advanced recycling techniques for secondary P or drawdown strategies for legacy P	Challenges
Secondary phosphorus resources				
Mining and fertilizer industry	6–12 Mt P yr^{-1} [1,2,8,64]	Disposal in landfills or coastal waters, or stacked on land	Pyrolysis, leaching and precipitation	High complexity and cost
Livestock manure	15–20 Mt P yr^{-1} [1]	Direct application (~90%)	Flocculation, settling, screw pressing, belt filtration, centrifugation and anaerobic digestion (and subsequent dissolved air flotation)	Large volumes produced only in a few regions Geographic disconnect between generation and use locations Dewatering is energy-intensive and transportation is logistically complex
Food waste	~1.2 Mt P yr^{-1} [1,59]	Landfill (~60%) Animal feed (5–10%)	Composting, anaerobic digestion and incineration	Low phosphorus concentration High heterogeneity of materials
Wastewater	~3.7 Mt P yr^{-1} [82,83]	Discharge into surface waters, irrigation and agricultural reuse[b]	Biological removal and chemical precipitation	Requires infrastructure Processes might substantially differ depending on waste characteristics and regions
Sewage sludge[a]	~3 Mt P yr^{-1} [86]	Landfill, direct application[b]	Incineration, pyrolysis and composting	Yuck factor Low phosphorus availability in sludge-derived products Chemically intensive
Sewage sludge ash[a]	0.13–0.22 Mt P yr^{-1} [194]	Landfill, direct application[b]	Chemical and thermochemical treatments	Energy- and chemically intensive High costs

Legacy phosphorus stocks				
In soil	~815 Mt P [96]	Accumulation, erosion and runoff	Phosphorus-mining crops, biostimulants, bioengineering, plant breeding and biofertilizers	Low bioavailability Geographical dispersion
In sediment	>2600 Mt P [55]	Accumulation	Direct application	Dredging lakes is costly and complex Contamination is possible

[a]The phosphorus reported in sewage sludge and sludge ash originates from the total phosphorus in wastewater. These values are not additive; instead, the phosphorus content in sludge and ash is contained within the original wastewater phosphorus flow. [b]Subject to local legislation. P, phosphorus.

Table 2. Strategic priorities for advancing phosphorus recycling and sustainability

Goal	Key developments needed	Research priorities	Methods and techniques
Minimize waste	Improve food waste management practices Redouble efforts to keep sewage clean to enable safe reuse of sludge Reduce industrial phosphorus losses during food processing	Investigate success factors in household food waste separation and reduction Study societal, economic and infrastructural barriers to source-separated sanitation Develop comprehensive national and regional phosphorus balances to quantify and locate key phosphorus losses	Behavioural analysis: surveys, interviews, smart bin sensor data analysis Spatial mapping: GIS mapping of waste and sanitation access patterns Economic evaluation: cost-effectiveness analysis, pilot incentive schemes Infrastructure and policy integration: collaboration with utilities, regulatory framework co-design Material flow analysis: mass balance studies, integration of corporate and national phosphorus data Modeling and prediction: nutrient dynamic models (APSIM or DNDC), machine learning for waste prediction
Reduce phosphorus runoff	Adopt more efficient fertilizer use practices Develop slow-release and enhanced-efficiency fertilizers Exploit legacy phosphorus in soil and sediment	Advance precision fertilization and controlled-release technologies Improve understanding of phosphorus mobility under different soil and climate conditions Quantify the effectiveness of cover crops in legacy phosphorus mobilization Assess the agronomic potential of phosphorus recovery from lake sediment	Fertilizer efficiency improvement: precision fertilization trials, slow-release fertilizer testing, meta-analysis under various conditions Sensor and technology integration: sensor-based fertilization systems, variable-rate application with drones or satellites Phosphorus movement tracking: lysimeter and field leaching studies Nutrient dynamics modelling: simulation using APSIM or DNDC models Legacy phosphorus mobilization: cover crop experiments, microbial and enzymatic pathway studies Sediment phosphorus recovery: collection and laboratory testing of sediment cores from eutrophic lakes
Enhance nutrient use efficiency	Introduce nutrient budgeting tools at the farm scale Increase farmer awareness of efficient phosphorus use Design more efficient and sustainable phosphorus fertilizers Improve phosphorus management on-farm	Evaluate policy instruments that promote balanced phosphorus inputs, such as nutrient caps, certification schemes Identify best practices and barriers in farmer education and extension programs Explore digital tools and decision-support systems for optimising farm-level nutrient use	Farm-scale nutrient planning: nutrient budgeting tools, whole-farm simulation (NuGIS, FarmDESIGN) Policy and governance evaluation: policy assessment (nutrient caps, certification), agent-based modelling of policy impacts Farmer education and outreach: surveys and/or interviews on extension strategies, identification of best practices and peer learning champions Digital tool development: decision-support systems, mobile apps, AI-powered nutrient management platforms

			Precision agriculture integration: incorporation of weather and soil data into recommendations, collaboration with ag-tech startups, integrate weather and soil data layers for precision recommendations Digital tool development: decision-support systems, mobile apps, AI-powered nutrient management platforms, co-designed farmer-friendly interfaces
Promote phosphorus recycling	Reduce land application of sewage sludge due to micropollutant concerns Adopt targeted phosphorus recovery (e.g. struvite and ash-derived products)	Investigate financial models and policy tools to reduce investment risk in phosphorus recovery technologies Support the harmonization and implementation of product standards, such as the EU Fertilising Products Regulation Research farmer perceptions and agronomic performance of recovered phosphorus products Develop certification schemes to increase market acceptance	Technology development and evaluation: techno-economic analysis of phosphorus recovery technologies, digital twin models for wastewater tracking Policy and financial instruments: financial model investigation, targeted subsidies, tax incentives, certification schemes, harmonization of product standards Farmer acceptance and agronomic testing: farmer field trials with recovered phosphorus products, surveys on farmer perceptions Governance and multi-actor collaboration: stakeholder platforms, comparative governance analysis (ESPP, UK and Germany), systems thinking tools (e.g. causal loop diagrams) Monitoring and regulatory frameworks: municipal monitoring programmes, micropollutant threshold co-definition with regulatory agencies Knowledge sharing and foresight: global case study repository, foresight workshops on scaling collaboration platforms
Foster transdisciplinary collaboration	Model new platforms on existing ones (e.g. ESPP, Dutch and German Nutrient Platforms and UK Phosphorus Transformation Strategy)	Evaluate the effectiveness and governance models of multi-stakeholder platforms Identify key success factors and lessons learned from regional initiatives Assess mechanisms for scaling and replicating collaborative governance structures	Governance analysis: evaluation of multi-stakeholder platform models, analysis of governance structures, funding and communication strategies Scaling and replication studies: assessment of scaling mechanisms, testing replicability via policy labs, publishing blueprints with adaptation guidelines Stakeholder engagement: interviews with platform coordinators and stakeholders, synthesis of lessons learned for guidelines Participatory methods: use of living laboratories, participatory foresight, and scenario-building for adaptive governance design International collaboration: organize workshops for model exchange and best practice sharing across regions

APSIM, Agricultural Production Systems sIMulator; DNDC, DeNitrification-DeComposition; ESPP, European Sustainable Phosphorus Platform.

Figure legends

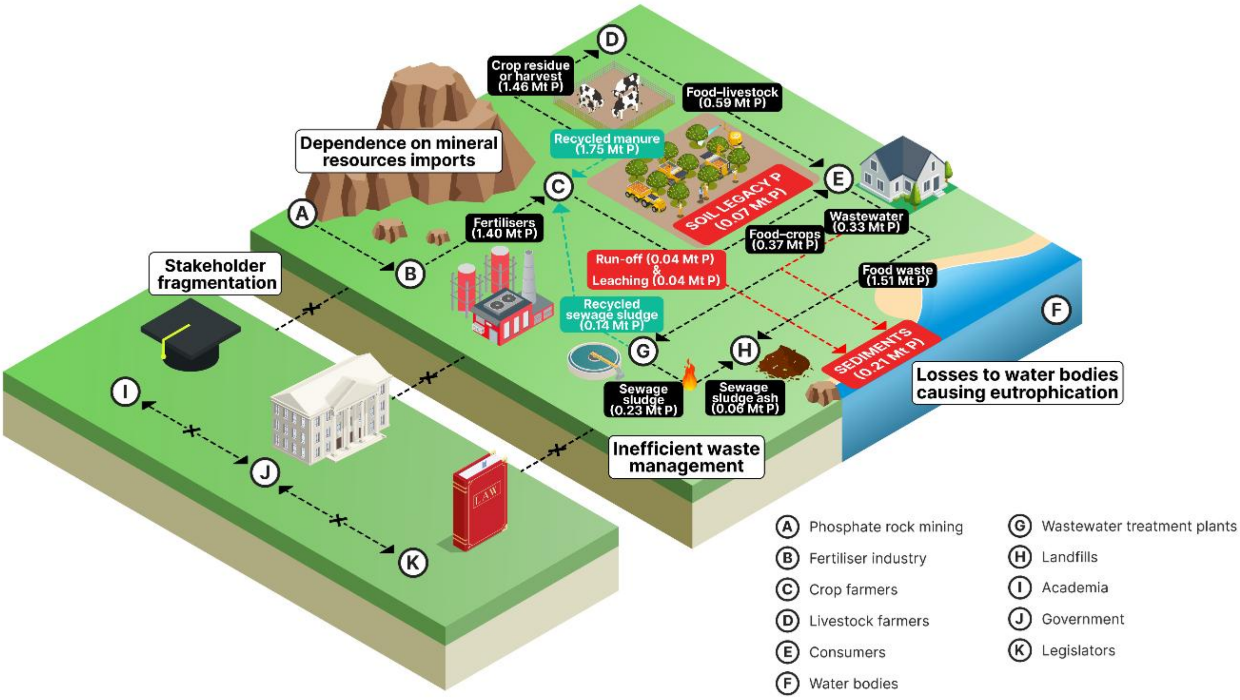

Fig. 1. Phosphorus cycle flows and challenges in the European Union. Phosphorus flows in the EU in 2005, based on data from[47]. The predominantly linear cycle begins with phosphate rock mining (mostly outside the EU), followed by phosphorus use in fertilizers, human and animal consumption, and eventual inefficient disposal as waste, leading to widespread losses to the environment as legacy phosphorus accumulates in soil and sediment. Partial recycling of phosphorus occurs through manure and sludge application in agriculture, but addressing environmental and health impacts remains technically and logistically challenging. No major advanced recycling efforts had been established when these data were collected. Collaboration-hindering stakeholder fragmentation is a major barrier to large-scale implementation of advanced phosphorus recycling initiatives.

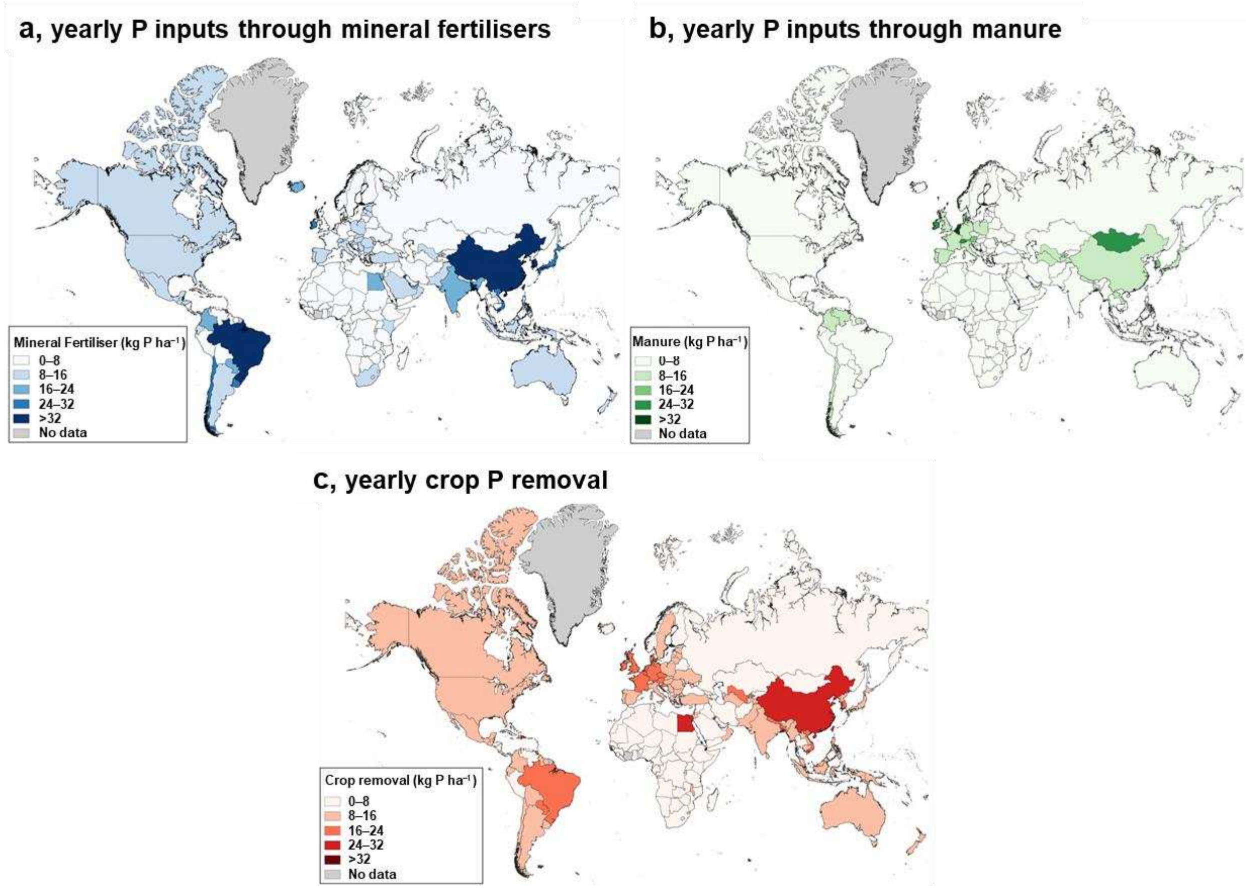

Fig. 2. Global phosphorus inputs and removals in agriculture. The major inputs of phosphorus in agriculture are through mineral fertilizer and manure application, whereas crop offtake is the main process of phosphorus removal. **a,** Global rates of mineral phosphorus fertilizer application. **b,** Global rates of manure application. **c,** Crop phosphorus removal. The maps highlight the uneven patterns of phosphorus consumption around the world, with disproportionally high phosphorus inputs in countries such as Brazil and China, higher manure application in Europe, China and Mongolia, and higher phosphorus uptakes in Europe despite low mineral phosphorus inputs, which is attributed mainly to legacy phosphorus drawdown. Based on data from ref.[48].

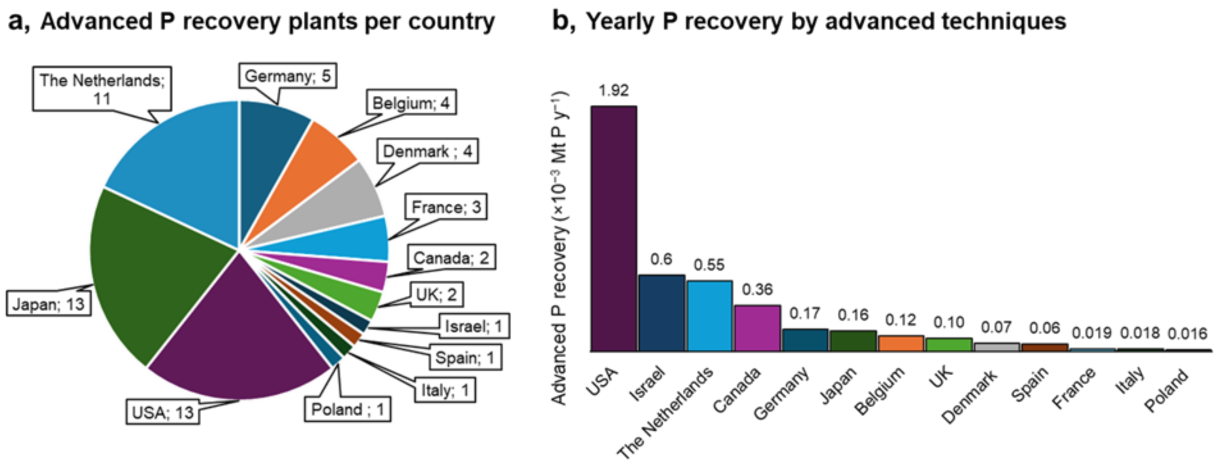

Fig. 3. Global distribution and recovery amounts of advanced phosphorus recovery plants. a, Number and distribution of operational advanced phosphorus recovery facilities in each country in 2023. **b,** Annual total phosphorus output by the 61 advanced P-recycling plants that reported their yields in 2016[88].

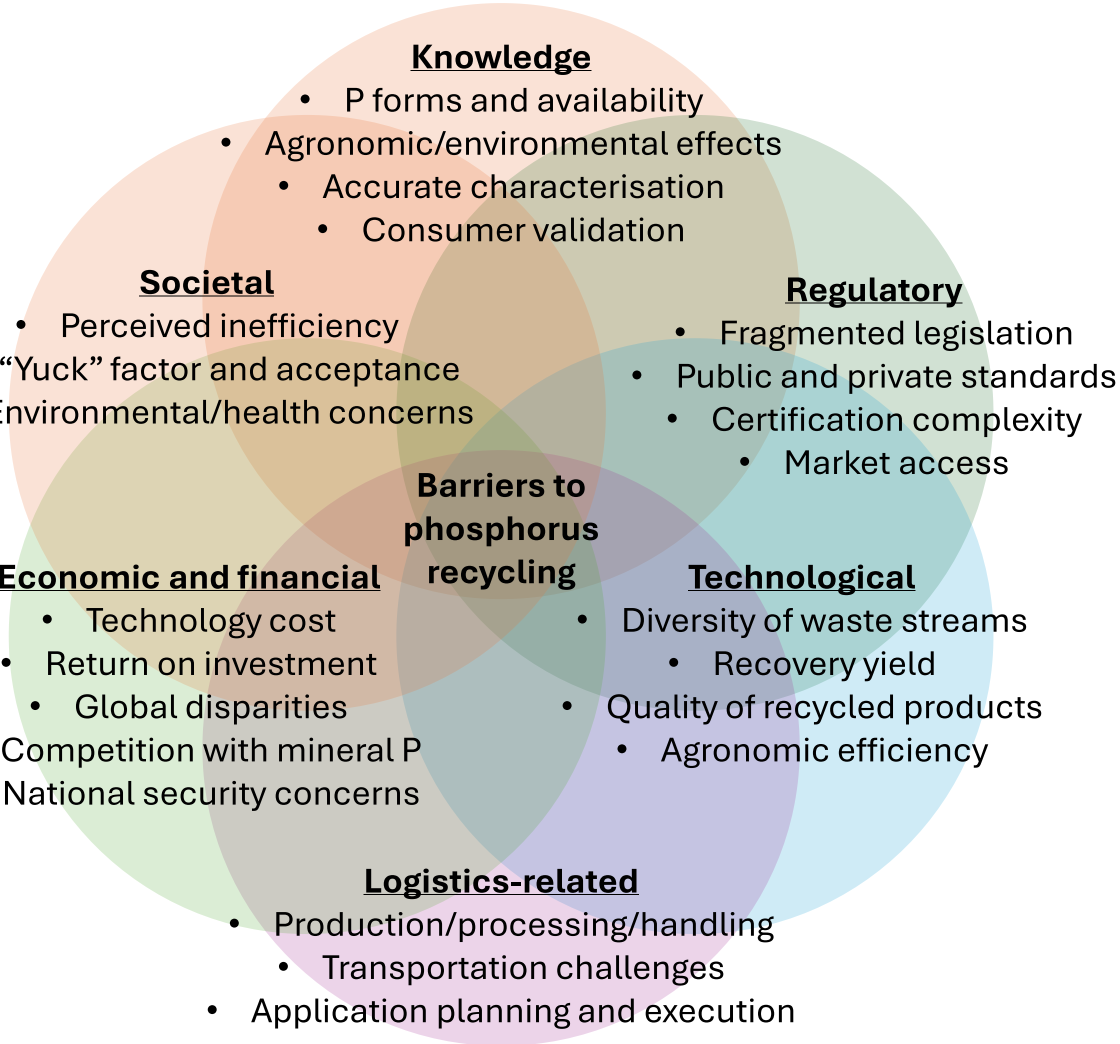

Fig. 4. Overview of key interconnected barriers to phosphorus recycling. Interconnected technological, economic and financial, regulatory, and societal barriers hinder phosphorus recycling. These barriers reinforce one another, sustain reliance on mineral phosphorus imports, contribute to inefficient waste management, and drive environmental phosphorus losses. Addressing them requires coordinated, cross-sector action to establish a more circular and sustainable phosphorus system.

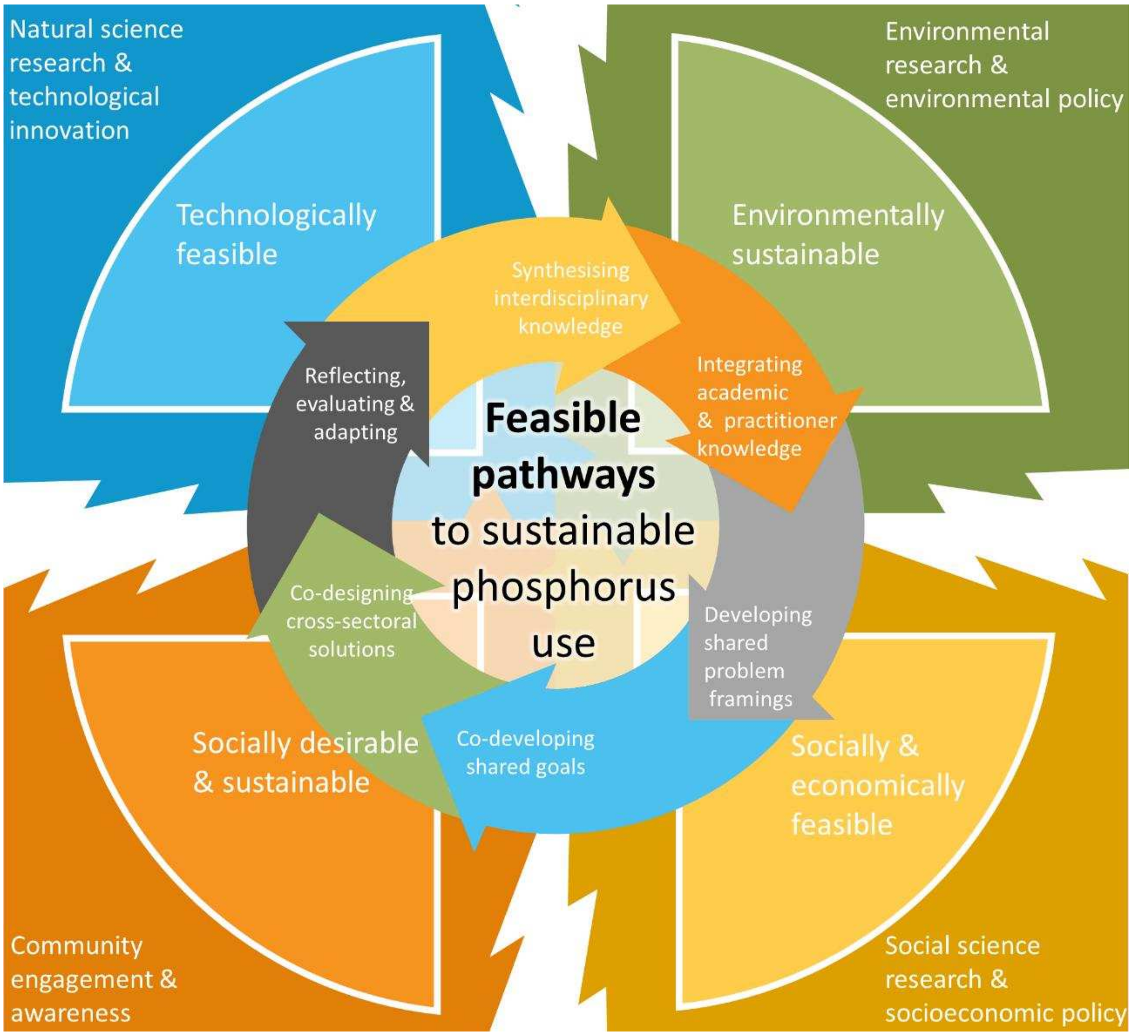

Fig. 4. Transdisciplinarity as a tool to overcome fragmentation through integration and stakeholder engagement. The role of a transdisciplinary approach to phosphorus management[193]. Fragmentation across research fields and sectors hinders the development of sustainable phosphorus pathways that are technologically, environmentally, and socially feasible. Transdisciplinary approaches grounded in stakeholder engagement can overcome this by integrating disciplines, sectors, and actors. Co-developing solutions with stakeholders increases buy-in and the chances of successful implementation.

Box 1. Strategies to overcome transdisciplinarity barriers in phosphorus stewardship

To strengthen transdisciplinary research, several strategies can be implemented. First, enhancing communication and coordination is crucial. This aim can be achieved by organizing regular workshops and meetings to connect stakeholders from different disciplines[195], alongside developing shared digital platforms to facilitate collaboration and information exchange[196]. Securing funding and resources is equally important. Advocating for dedicated funding programmes tailored to transdisciplinary research[195] and encouraging public–private partnerships to pool resources[196] can help address this need. Integrating knowledge can be supported by establishing interdisciplinary training programmes, equipping researchers with the skills to synthesize diverse expertise[195], and developing collaborative frameworks[196]. Institutional support also has a key role. Policy reforms that prioritize transdisciplinary efforts[195] and institutional incentives that reward participation[196] can create a more supportive environment. Finally, stakeholder engagement must be prioritized. Inclusive decision-making processes ensure that all relevant actors, including local communities, are actively involved[195], and capacity-building initiatives empower stakeholders to contribute meaningfully to knowledge production[196]. Together, these actions can create a robust foundation for transdisciplinary collaboration, ultimately leading to more innovative and impactful outcomes.

eToC blurb

Achieving phosphorus circularity is a key challenge to realizing sustainable phosphorus use, and recycling is a major route to accomplish this goal. This Review explores global barriers to phosphorus recycling and discusses approaches to overcome the technical, economic and societal challenges in attaining sustainable phosphorus management.