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Article

Sustainable Phosphorus Measures: Strategies and Technologies for Achieving Phosphorus Security

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Abstract: Phosphorus underpins the world's food systems by ensuring soil fertility, maximising crop yields, supporting farmer livelihoods and ultimately food security. Yet increasing concerns around long-term availability and accessibility of the world's main source of phosphorus—phosphate rock, means there is a need to investigate sustainable measures to buffer the world's food systems against the long and short-term impacts of global phosphorus scarcity. While the timeline of phosphorus scarcity is contested, there is consensus that more efficient use and recycling of phosphorus is required. While the agricultural sector will be crucial in achieving this, sustainable phosphorus measures in sectors upstream and downstream of agriculture from mine to fork will also need to be addressed. This paper presents a comprehensive classification of all potential phosphorus supply- and demand-side measures to meet long-term phosphorus needs for food production. Examples range from increasing efficiency in the agricultural and mining sector, to technologies for recovering phosphorus from urine and food waste. Such measures are often undertaken in isolation from one another rather than linked in an integrated strategy. This integrated approach will enable scientists and policy-makers to take a systematic approach when identifying potential sustainable phosphorus measures. If a systematic approach is not taken, there is a risk of inappropriate investment in research and implementation of technologies and that will not ultimately ensure sufficient access to phosphorus to produce food in the future. The paper concludes by introducing a framework to assess and compare sustainable phosphorus measures and to determine the least cost options in a given context.

Keywords: sustainable phosphorus measures; efficiency; recycling; food production and consumption system; food security; least-cost options

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1. Introduction

The element phosphorus underpins our ability to produce food: it has no substitute in crop growth and cannot be manufactured [1]. Indeed, the use of chemical fertilizers has contributed to feeding billions of people over the last half-century by boosting crop yields [2]. Yet the world's main source of phosphorus fertilizers—phosphate rock—is a non-renewable resource that is becoming increasingly scarce and expensive [3]. If no changes are made to the current trajectory, long-term demand for phosphorus will increase to feed a growing global population, meet changing diets towards more meat and dairy foods and biofuel crop demand. At the same time, peak phosphorus is estimated to occur this century, possibly before 2040, after which demand will outstrip supply [3–5]. The longevity of phosphate rock reserves is debated and ranges from 30–300 years depending on assumptions such as demand rate, P concentrations and economic viability [6–9]. However there is consensus that phosphate rock ore grades are in decline, physical access to ores will become increasingly difficult, energy costs and waste generation are likely to increase [6,8]. Phosphate prices are expected to increase in the long-term as lower ore grades are mined and more expensive technology employed [7,8] and in the short term price spikes such as the 2008 800% price rise could occur again [10]. Many of the world's agricultural soils with naturally low phosphorus availability (*i.e.*, where the phosphorus is tightly bound or fixed to other compounds) are in developing country regions where farmers have low purchasing power to access fertilizer markets [11,12]. Further, remaining global phosphate reserves are controlled by only a few countries, including Morocco, Iraq, China, Algeria and Syria—70% by Morocco alone [13]. Such an uneven distribution of one of the world's most important resources presents significant risks and warrants the attention of national leaders. Effective institutional structures such as policies or monitoring frameworks are lacking at the international and national level to ensure long-term availability and accessibility of phosphorus for food security [11]. However awareness of this important global challenge has increased over the past several years [5,14,15].

Phosphorus in the global food system typically begins in the mining sector when phosphate rock is mined, cleaned and transferred to the fertilizer industry where it is processed chemically into phosphate fertilisers. Such fertilizers are traded globally and then enter the agricultural sector where they are applied regularly to fields and pastures, where some of the phosphorus is taken up by plant roots and livestock. Phosphorus then leaves the fields in crop harvests, animals' bodies or eroded soil, or remains in crop residues, soils and manures. The food sector then processes phosphorus-containing crops and animal products into vegetal (cereals, horticultural crops) and animal based foods such as meat, milk, eggs and fish. Some of these products are consumed by the human population with the remainder predominantly ending up in organic waste destined for landfills or compost heaps. Almost all of the phosphorus in food consumed by humans leaves the body in urine and faeces. This enters the wastewater sector (except in the case of open defecation or onsite reuse) where it undergoes some form of treatment and largely ends up in oceans, rivers or on land [3,16].

Ultimately, only one-fifth of the phosphorus mined for food production finds its way into the food consumed by the global population each year [3]. The current food production and consumption system is extremely inefficient with respect to phosphorus use. Some of these are "permanent" losses, such as phosphorus in manure runoff to waterways, while other losses are "temporary", such as residual fertilizer phosphorus remaining in soils that is potentially available to plants in subsequent years [17,18]. Phosphorus is lost at all stages, including during mining, fertilizer production, crop production, livestock production, food processing and distribution and food consumption. Some of these losses are unavoidable (e.g., inedible crop fractions such as banana peels or corn husks) although some waste streams can be recycled for their phosphorus content. In any case, some of the losses can be avoided in the first place (such as fertilizer spillages or food spoilage) as they are due to inefficient practices and these can be the target of sustainable demand measures that increase efficiency. In general, preventing resource losses first is typically more energy and economically efficient than recycling, across a number of resource and energy sectors [19]. Increasing prices often act as a trigger for reducing waste through improved efficiency, but there are numerous examples where market failure prevents the most cost-effective options being implemented [20]. Substantial opportunities also exist for not only increasing the efficiency of the food production and consumption system, but to also rethink the way we use phosphorus to achieve nutritional security for the global population (such as more phosphorus-efficient diets and producing food closer to the demand).

While there is still much debate regarding the longevity of phosphate reserves, scientists and industry agree that there is a strong need for increased recycling and efficient use of phosphorus throughout the food system [7–9]. There is a need to systematically identify and compare measures that can deliver outcomes towards phosphorus security. An integrated approach including a suite of measures is required to buffer the world's food systems against the long and short-term impacts of global phosphorus scarcity. While the agricultural sector will be crucial, sustainable phosphorus measures in sectors upstream and downstream of agriculture from mine to fork will also need to be addressed. Figure 1 indicates how a combination of supply and demand measures can together ensure long-term global phosphorus demand—and hence food demand—can be met.

Due to the complexity of the global phosphorus scarcity challenge, the objectives of phosphorus security are diverse yet an overarching aim is to ensure that all farmers have sufficient access to phosphorus to produce enough food to feed the global population whilst maintaining ecological and social integrity [11]. Maximising the life-span of finite phosphate rock resources is also an important goal. Phosphorus security goals might therefore include:

- Increase number of people fed per tonne phosphorus input, or, reduce total phosphorus demand while maintaining food/agricultural output;
- Reduce dependence on phosphorus imports (to reduce vulnerability to geopolitical dynamics and thereby increasing long-term access to phosphorus);
- Ensure healthy soils (no phosphorus-deficiency, no phosphorus accumulation, balanced nutrition and presence of organic matter);

- Ensure farmers needs are met (e.g., maintaining or increasing productivity; ensuring access to phosphorus fertilisers);
- Reduce losses and wastage where avoidable;
- Reduce eutrophication and pollution by preventing phosphorus from the food system from entering waterways.

Figure 1. Sustainable phosphorus supply and demand measures for meeting long-term future global food demand. Adapted from Cordell *et al.* [21].

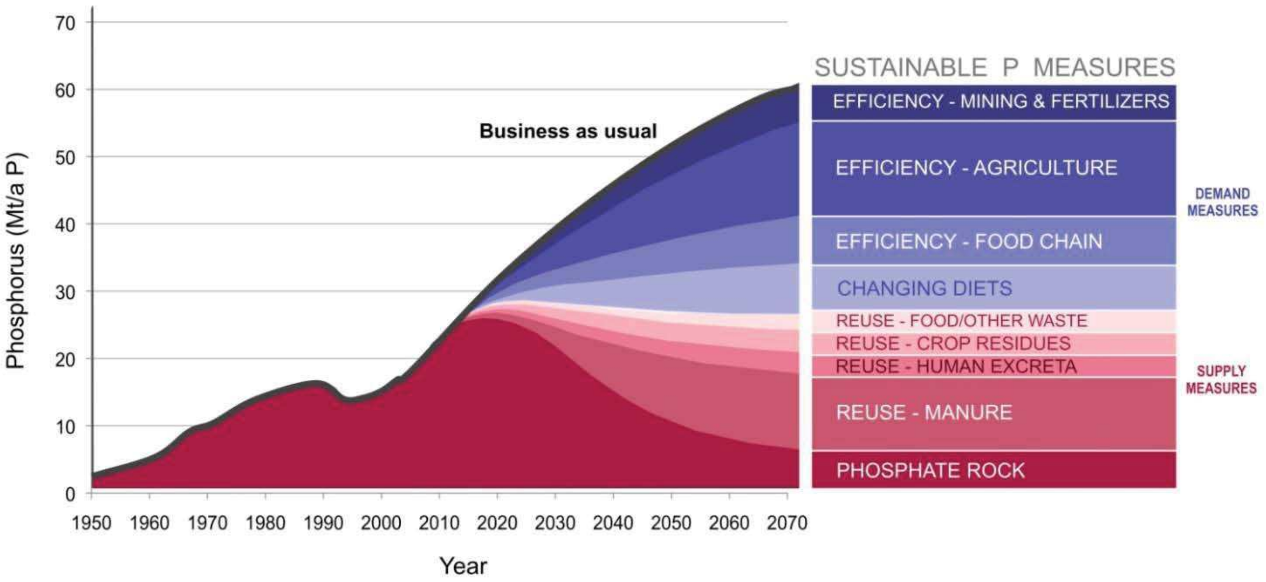


Table 1 highlights which sustainable phosphorus measures can meet which phosphorus security goals.

Table 1. Identification of which actions (sustainable phosphorus measures) can address which goals (phosphorus security). Adapted from Cordell *et al.* [22].

GOALS: Phosphorus security	**ACTIONS: sustainable phosphorus measures**				
	Reconsider profile of agriculture *	Diversify P sources **	Reconsider diets towards P-efficient foods	Increase phosphorus use efficiency	Increase recycling of phosphorus
Increase number of people fed per tonne P input, or reduce total P demand while maintaining food/agricultural output	★		★	★	
Reduce dependence on P imports	★	★	★	★	★
Ensure healthy soils				★	★
Ensure farmers needs are met	★	★		★	
Reduce losses and wastage		★		★	★
Reduce eutrophication & pollution				★	★

* That is, breakdown of crop types (e.g., wheat, canola, sugarcane) and livestock types (e.g., intensive, grazed, *etc.*), including proportion of exports and imports; ** phosphorus from rock and other organic sources.

This paper sets out to firstly develop a typology or classification of sustainable phosphorus measures; secondly to identify and review such measures by sector; and finally to introduce a framework for systematically assessing and comparing these measures as a means to determine the least-cost sustainable phosphorus options for a given country or context.

2. Classifying Sustainable Phosphorus Measures

There are many different ways by which sustainable phosphorus measures can be classified [21]. "Recycling and efficiency" are often referred to as twin solutions, however these exclude other sustainable measures at a higher system level such as reducing overall demand through changing diets or even the use of other sources of phosphorus such as algae. For the purpose of this paper, we have used "supply" and "demand" measures as the highest order typology. We have also categorised the measures by sector so they are relevant to individual stakeholder groups. Table 2 provides a toolbox of sustainable phosphorus measures classified as supply or demand measures and by sector. These are described in greater detail in Section 3.

There is no single solution to meeting the world's future phosphorus needs for food demand. Rather, an integrated approach that involves the right combination of supply and demand measures in key sectors of the food system will be required [21]. Table 2 allows assessment of phosphorus measures classified either by type (columns) or by sector (rows).

2.1. Supply Measures

Supply measures deliver a phosphorus source for use as a fertilizer. These can include recycled phosphorus within the food system (such as composted food waste) which means it is recovered from one sector and reused in agriculture as a fertilizer, or new sources (such as phosphate rock or algae) which means it is sourced from outside of the food system and enters the agricultural sector. "Renewable" phosphate fertilizer refers to a renewable resource (as opposed to a non-renewable resource like phosphate rock) and could include either a used/recycled source such as manure, or a new source such as algae that has grown from nutrients external to the food system such as brines and saltwater [23].

Phosphorus sources vary widely in terms of phosphorus concentration, chemical form and state (solid, liquid or sludge). From a sustainability perspective, important considerations include: life cycle energy associated with sourcing, transporting and using phosphorus; level of contaminants; phosphorus concentration; other material/chemical inputs; bioavailability to plant roots, usability for farmers; long-term availability and accessibility to farmers; and reliability of quality and quantity [24].

Table 2. Toolbox of sustainable phosphorus measures classified as supply and demand measures and by sector.

Sector	**SUPPLY MEASURE (S)**		**DEMAND MEASURE (D)**	
	Recycling (S1)	**New source (S2)**	**Efficiency (D1)**	**Reduce demand (D2)**
Mining (M)	MS1.1—mine tailings [h]	MS2.1—phosphate rock [h]	MD1.1—reduce avoidable losses	MD2.1—*(all other measures)*
Fertilizer (F)	FS1.1—phosphogypsum [h]	FS2.1—algae, seaweed	FD1.1—reduce avoidable losses	FD2.1—*(AD2, LD2, PD2)*
Agriculture (A)	AS1.1—crop waste [b,d,e] AS1.2—*(LS1, PS1, WS1)*	AS2.1—*(FS2)* AS2.2—green manure	AD1.1—fertilizer placement AD1.2—application time AD1.3—application rate AD1.4—soil testing AD1.5—erosion reduction AD1.6—microbial inoculants	AD2.1—plant selection AD2.2—improved soil characteristics
Livestock & Fisheries (L)	LS1.1—manure [a,b,f] LS1.2—bone [a,d] LS1.3—blood [a] LS1.4—fish [a]	LS2.1—phosphate rock (supplements) [h]	LD1.1—fertilizer placement LD1.2—application time LD1.3—application rate LD1.4—soil testing LD1.5—erosion reduction LD1.6—microbial inoculants LD1.7—phytase enrichment LD1.8—manure P reduction LD1.9—wastewater management	LD2.1—plant selection LD2.2—improved soil characteristics LD2.3—animal selection LD2.4—changing diets
Food production (P)	PS1.1—food production waste PS1.2—cooked food waste	PS2.1—phosphate rock (additives) [h]	PD1.1—reduce avoidable losses PD1.2—producing food closer to demand PD1.3—consumer food planning/preparation	PD2.1—reduce P-intensive diets PD2.2—reduce per capita overconsumption PD2.3—healthy bodies PD2.4—minimize use of P additives
Wastewater & human excreta (W)	WS1.1—urine [a,c] WS1.2—faeces [b,c,d,h] WS1.3—greywater [c, h] WS1.4—untreated wastewater [a] WS1.5—treated effluent [a] WS1.6—struvite [c] WS1.7—biosolids [a,b,f,h] WS1.8—sludge ash [d]	N/A	WD1.1—repairing cracked pipes WD1.2—minimizing sewer overflows WD1.3—soil management WD1.4—avoid dumping biosolids in water WD1.5—reduce spreading biosolids on non-ag land	N/A

Recycled via: [a] direct reuse, [b] compost, [c] precipitation, [d] incineration, [e] fermentation, [f] dewatering, [h] other chemical treatment.

2.2. Demand Measures

Demand measures seek to reduce total phosphorus demand while maintaining outputs, or increase productivity by increasing outputs per unit of input. Such measures vary widely and can include:

- reducing avoidable losses and wastage, such as food spoilage during food processing and distribution). Schroder *et al.* [17] present a typology of phosphorus losses, differentiating between permanent and temporary losses and hence sustainable management responses;
- increasing efficiency, such as phosphorus uptake by crop roots; or
- reducing the total phosphorus demand through changing diets towards food that require less phosphorus input per nutritional output (*i.e.*, reversing current trends towards meat and dairy as emerging economies like China and India increase in affluence [25] and reduce the already high rate of meat and dairy consumption in developed countries).

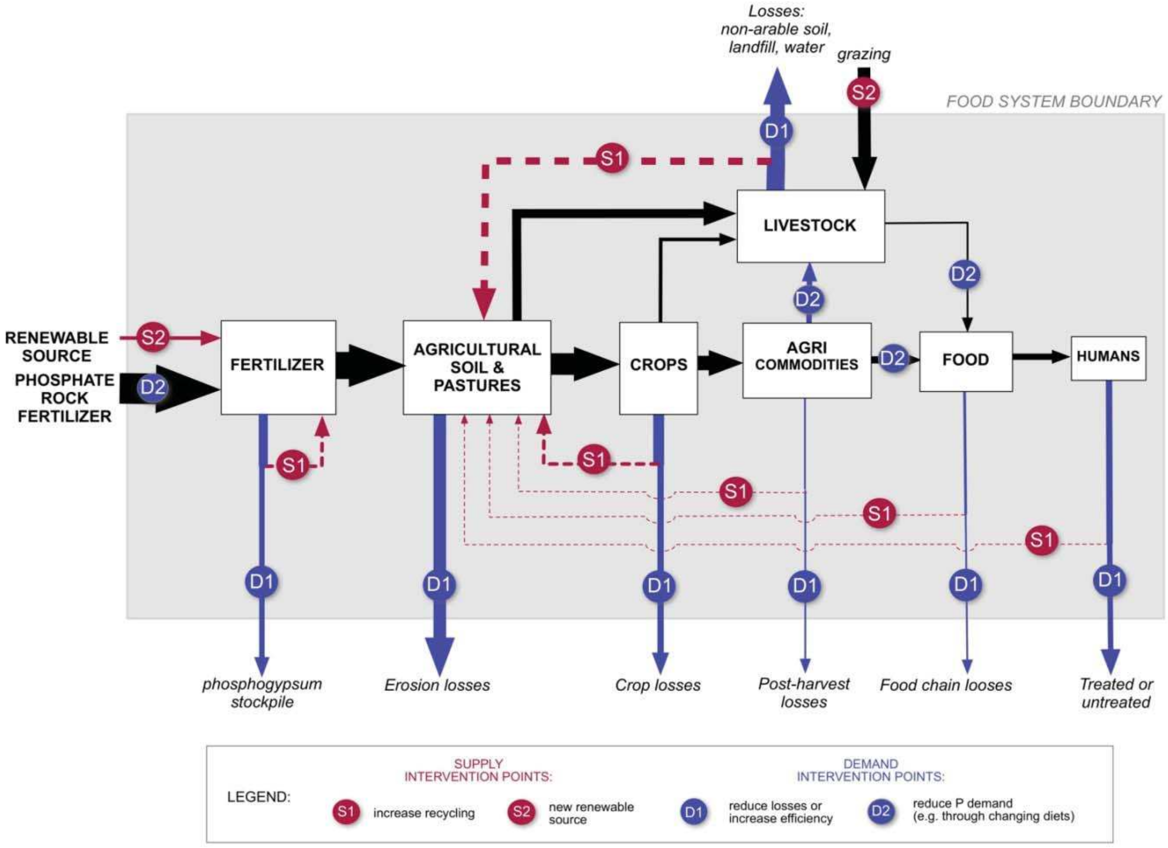
Phosphorus is essential for crop growth hence there will always be a demand for phosphorus. Indeed, 90% of the current phosphorus use is for food production, predominantly fertilisers (82%), animal feed supplements (7%) and food additives (2%–3%) [26]. For these reasons, this paper focuses on the food system.

2.3. A Systems Approach

It is also constructive to consider sustainable phosphorus measures as intervention points within the food system. This enables national phosphorus substance flow analyses to be directly linked to sustainable measures [24,27]. Figure 2 indicates the two types of supply measures—increasing recycling (S1) and new renewable sources (S2); and two types of demand measures—reducing avoidable losses and increasing efficiency (D1) and reducing phosphorus demand through changing diets (D2).

As with any systems analysis, it is important to identify synergies [28] and simultaneously avoid double counting [17]. Recycling by definition involves taking a resource from one sector (recovery) and using it in another sector (reuse). For example, recycling phosphorus from wastewater sector to agriculture should not be counted in both sectors [21]. For the purpose of this paper, we classify a recycling measure as the sector from which the phosphorus was sourced (in this example, the wastewater sector) and indicate the reuse in the recipient sector (in this case the agricultural sector) in parentheses. Similarly, increasing efficiency in one sector (such as livestock sector), might decrease the overall phosphate rock fertilizer demand, however the latter should only indicate this in parentheses.

Figure 2. Sustainable phosphorus measures indicated as intervention points in the food system. These are classified as either supply measures—increasing recycling (S1) and new renewable sources (S2); or demand measures reducing avoidable losses or increasing efficiency (D1) and reducing phosphorus demand through changing diets (D2). Adapted from Cordell *et al.* [24].



3. Sustainable Phosphorus Measures by Sector

This section outlines the current inefficiencies in phosphorus use and identifies the potential range of sustainable demand measures (D1 and D2) and supply measures (S1 and S2) within each key sector (summarized in Table 2). Where relevant, other important aspects are highlighted, including: institutional issues (such as stakeholder roles and responsibilities), life cycle costs, logistics, synergies and conflicts and examples.

3.1. Mining Sector

Mining phosphate rock for use in fertilizers has contributed to feeding billions of people over the past half century. However phosphate rock mining has been the focus of many recent studies and debates, particularly in relation to phosphate rock as a finite resource that is geographically concentrated, contains heavy metals like cadmium and radioactive elements like radium and thorium and increasing requirement for more energy and costs to produce the same amount of P per ton of rock [3,9,17]. Hence the overarching needs to minimize phosphate rock use and diversify sources of phosphorus. Investing in sustainable phosphorus measures in the phosphate mining sector can therefore increase longevity of finite supplies, increase productivity of the industry, reduce water and land pollution and improve the livelihoods of local communities.

While UNEP [29] identify the environmental impacts of phosphate rock mining, less is known about specific phosphorus losses and wastage and hence opportunities for phosphorus efficiency gains and recycling in the mining sector. This lack of public knowledge may be a result of the lack of transparency within the industry, the fact that processes have not changed over the past half-decade, or, the exclusion of the mining sector from many recent phosphorus flow analyses because most of the countries are importing (not producing) countries [30]. Phosphorus is predominantly lost in the mining sector via beneficiation (concentration) process when iron phosphate and other contaminants are removed and via spillages during storage and transport [29]. A recent study undertaken by the International Fertiliser Industry Association found that average losses during mining, beneficiation and handling are in the order of 15%–30% [26], while others have estimated slightly higher losses up to 50% [17].

There has been little incentive until recently to minimize phosphorus losses in mining operations, however the lowering grade of phosphate ore, increasing input costs and greater spotlight on the industry are likely to trigger such efficiency measures [26]. It is unclear how much of these losses can be avoided via efficiency demand measures (MD1) through improved technology and management (such as reducing spillages). Most supply and demand measures in other sectors (discussed in Sections 3.2–3.6) will ultimately reduce the overall demand for mined phosphate rock (MD2).

On the supply side, phosphorus can potentially be recovered (MS1) from mine waste [17,29]. Increased prices and scarcity has sparked new interest and investment in exploration of new phosphate rock deposits and commissioning of new phosphate rock mines (MS2)—most notably in Saudi Arabia, Australia and seafloor sediments off the coast of Namibia [31–33]. However such sources will face the same pressures as current phosphate rock mining, including finite nature of the source, increasing energy costs, increasing volume of waste generation, radioactive waste generation and potential geopolitical dynamics [4,8].

Other potential sustainable measures in the phosphate-mining sector include [11,17,29]:

- Minimizing local environmental impacts, such as pollution/breaching of tailings dams;
- Investing in efficient technologies, such as for cadmium removal;
- Corporate social responsibility, particularly in the disputed region of Western Sahara. While ownership of the region is disputed, Morocco currently occupies Western Sahara and controls that region's extensive phosphate rock reserves in defiance of UN resolutions [34,35]. Trading with Moroccan authorities for Western Sahara's phosphate rock is condemned by the UN, and importing phosphate rock via Morocco has been boycotted by several Scandinavian firms [36];
- Contribution of the industry to mitigating downstream impacts, in accordance with the principles and frameworks of Extended Producer Responsibility.

3.2. Fertilizer Sector

Commercial phosphate fertilizers provide a range of uniform products of high phosphorus concentration in a plant-available form. Such phosphate fertilizers today are predominantly produced by the "acid route", where sulphuric acid is reacted with phosphate rock to yield the more concentrated and plant-available form phosphoric acid, the main intermediate by which phosphate fertilizers are ultimately produced [26]. Commercial phosphate fertilizers include: Single superphoshate (SSP), Triple superphosphate (TSP), Monoammonium phosphate (MAP), diammonium phosphate (DAP) and NPK fertilizers.

The main phosphorus loss in this sector is associated with the by-product phosphogypsum (Figure 3), which prevents radioactive isotopes associated with Uranium and Thorium from ending up in the finished fertilizer product. However, each tonne of processed phosphoric acid generates four to five tonnes of phosphogypsum [37]. Radioactivity levels of phosphogypsum are considered too high by some authorities for reuse as gypsum and the by-product must be stockpiled as a dry or wet stack. The world's phosphogypsum stacks are estimated to increase by some 700,000 tons of elemental phosphorus each year [26]. This amount is almost a quarter of the phosphorus contained in the food consumed each year by 7 billion people.

Figure 3. Phosphogypsum stockpile in Florida—byproduct from phosphate fertilizer production often considered too radioactive for reuse (Image from US Environmental Protection Agency).

On the supply side, there are large potential opportunities to recover phosphorus from phosphogypsum (FS1) in terms of quantity. However, the technical and commercial feasibility of safely extracting the large quantities of phosphorus currently "locked up" in phosphogypsum stockpiles is currently unclear and under investigation [38]. The International Phosphogypsum Working Group (an industry partnership) investigated the risks of using phosphogypsum *versus* the risks of not using phosphogypsum and found that beneficial reuse is most optimal if certain principles are adhered to such as "coherent and consistent global standards in overseeing or regulating essential industries" [38]. However this includes reuse for non-food purposes such as road fill or construction material which would render it unavailable for food/fertilizer use.

Other supply measures in the phosphate fertilizer sector might include renewable phosphate fertilizers sourced from organic waste (FS1) or new sources such as algae (FS2) [15]. The profile of the fertilizer industry currently largely represents phosphate fertilizers sourced from non-renewable phosphate rock, hence there is a need for technical, financial and institutional support for the development of renewable fertilizers. Such diversification can have benefits for multiple stakeholders, including strategically for the fertilizer industry itself, for farmers and for national food security.

Indeed, a 2012 EU parliamentary recommendation called for "appropriate criteria and start pilot projects for…phosphorus, with a view to achieving virtually 100% reuse by 2020 and optimizing their use and recycling; emphasizes that such pilot projects should receive direct funding from the EU" [39].

Over the last two decades, the fertilizer industry has played a role in assisting farmers with the importance of fertilizer use and efficient fertilizer application technique to reduce phosphorus loss via erosion that can potentially pollute waterways and lead to algal blooms (such as the Fertilizer Best Management Practices [40] or the Fertilizer Industry Federation of Australia's Fertcare program [41]). Given the greater interest and awareness in other sustainability challenges surrounding phosphorus fertilizer use (as outlined in Section 1), the fertilizer industry could broader support an integrated approach that focuses more on renewable fertilizers, optimising soil fertility and farmer access to phosphorus. The current fertilizer demand only represents market demand, and excludes up to a billion of the world's farmers who currently don't have sufficient purchasing power to access fertilizer markets. Many of these farmers are subsistence farmers in Sub-Saharan Africa, South East Asia and Latin America working with soils that are phosphorus-deficient or have a high phosphorus-retention potential and with low food security status [12,42].

The largest efficiency demand measures in the fertilizer sector (FDI) are likely to be around reducing production and transport losses or producing fertilizers more efficiently such that more phosphorus ends up in the final product. However there is little publicly available data on efficient phosphate "production" rather than efficient "use".

3.3. Agricultural Sector

The agricultural sector is at the heart of phosphorus use. Plants roots can only access their vital phosphorus supplies via dissolved phosphorus in soil solution [1]. Phosphorus inputs include fertilizers, manure, crop residues and the existing soil "stock", while outputs include agricultural products, runoff and ash [40]. Soil phosphorus can move back and forth on a continuum between being strongly bonded and hence inaccessible to plant roots through to being immediately available for root uptake [18]. Phosphorus soil chemistry is highly complex and different agricultural soils vary widely in phosphorus status and dynamics due to geology and soil type, land use and management, history of fertilizer use (for example areas with previous decades of over application may exhibit accumulation of phosphorus, while areas with lack of application might have phosphorus deficiencies) [12,18,43]. For these reasons, optimizing phosphorus use in agriculture is complex. Cakmak [44] estimates that approximately two thirds of the world's agriculture soils are phosphorus deficient. In Africa, Smaling *et al.* [45] estimated that agricultural soils were being depleted at a rate of 2.5 kg/ha/a, owing to extremely low fertilizer application rates—as low as 5 kg/ha in Sub-Saharan Africa [46]—due to high cost and low accessibility [9]. This stresses the importance of access to fertilizers and hence boosting soil fertility in these regions. Meanwhile soils in Western Europe have been accumulating phosphorus for decades because farmers apply more phosphorus than is removed each year. While different phosphorus management strategies might be required in different parts of the world, it is important that once critical soil phosphorus levels have been reached, soils are replenished at a phosphorus rate equal to what is being removed during harvest [47].

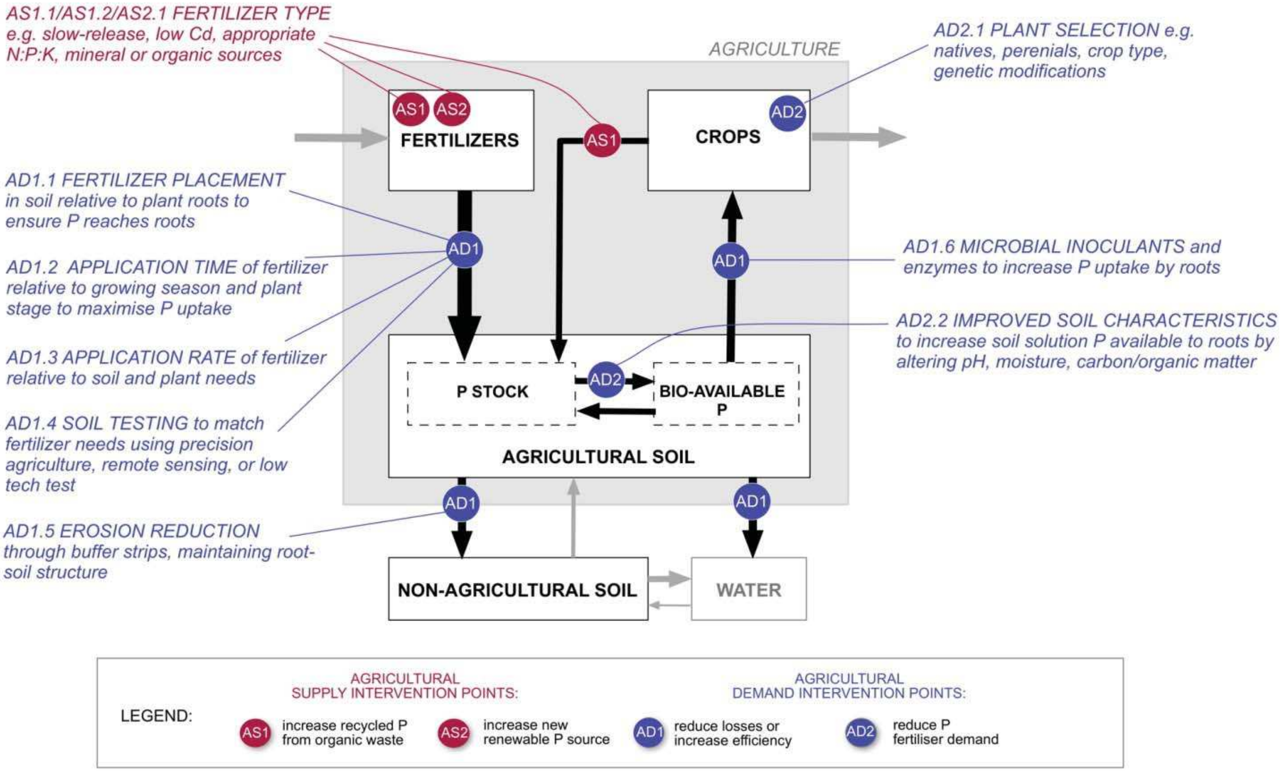
Whilst accurately calculating phosphorus use efficiency in a given agricultural system is fraught with difficulty [44], most systems have the potential for large improvements. The current level of efficiency varies widely between regions, and typically only 15%–30% of the applied fertilizer phosphorus reaches the crop [47], hence there is still potential for new innovations to increase crop phosphorus use efficiency. That is, increasing crop yields per unit input of phosphorus. Sustainable phosphorus measures in the agricultural sector—particularly improving phosphorus use efficiency—can substantially reduce the overall demand for phosphorus. Further, such measures can increase agricultural productivity, reduce deleterious environmental impacts on water bodies, avoid upstream energy costs and reduce farmer vulnerability to fertilizer price shocks thereby supporting farmer livelihoods.

For over a decade, the UNs Food & Agricultural Organization (FAO) and the international fertilizer industry (IFA) have called for more integrated nutrient management (such as the 4Rs) that ensures crop productivity through optimizing soil fertility and meeting nutrient needs from a range of organic and inorganic sources [40,47–49]. (The Global “4R” Nutrient Stewardship Framework refers to applying the right fertilizer product in the right rate, and the right time and in the right place [42].) Farming approaches such as organic farming, permaculture and conservation farming also all aim to minimize nutrient losses and to create close-looped nutrient cycles, thereby requiring zero or minimal external fertilizer inputs [50–52]. Figure 4 indicates the location of different intervention points in the agricultural sector where sustainable phosphorus demand and supply measures can systematically be implemented. These include:

- *fertilizer selection* to optimize the bioavailability of phosphorus (AS1.1, AS1.2, AS2.1);
- *fertilizer use* to maximize plant root’s opportunity to take up the phosphorus (AD1.1-AD1.4);
- *crop selection* to maximize plants ability to access more soil phosphorus or yield more crop per phosphorus accessed (AD2.1); and
- *soil management* to (a) ensure soil phosphorus is in solution and hence readily available to plant roots when they need it (AD1.6, AD2.2) and (b) to minimize permanent loss of soil phosphorus via wind and water erosion (AD1.5).

On the supply side, fertilizer selection (AS1, AS2) refers not only to the selection of appropriate phosphorus fertilizers in a form which maximizes the bioavailability of phosphorus to plant roots, but also in a form which is acceptable from a farmer perspective in terms of ease of handling and storage, market availability, odour and safety and environmental point of view as noted in Section 2. Phosphorus nutrients can be formally processed into fertilizers with consistent characteristics (ranging from phosphate rock-based high-analysis fertilizers like DAP [46] to chemically precipitated struvite from wastewater) or informally, such as direct integration of crop residues, direct application of manures [44] or even direct use of human urine [53]. The latter are typically less expensive and used locally however are not necessarily in a consistent and reliable form and hence makes precise application of the right amount of nutrients challenging. It is important that crop residues such as straw, husks, and stalks can be ploughed back into the soils after harvest (AS1.1), for their soil conditioning and fertilizer value (0.02%–0.3% P) [47]. Around 40% of the 5 Mt of P in crop residues generated annually are currently reused for their fertilizer value [16]. The remainder is used for feed, fuel, roofing bedding, sold or disposed of through burning or other means. New competing uses of crop residues such as biochar could potentially remove the phosphorus from the food system unless intentionally returned [24].

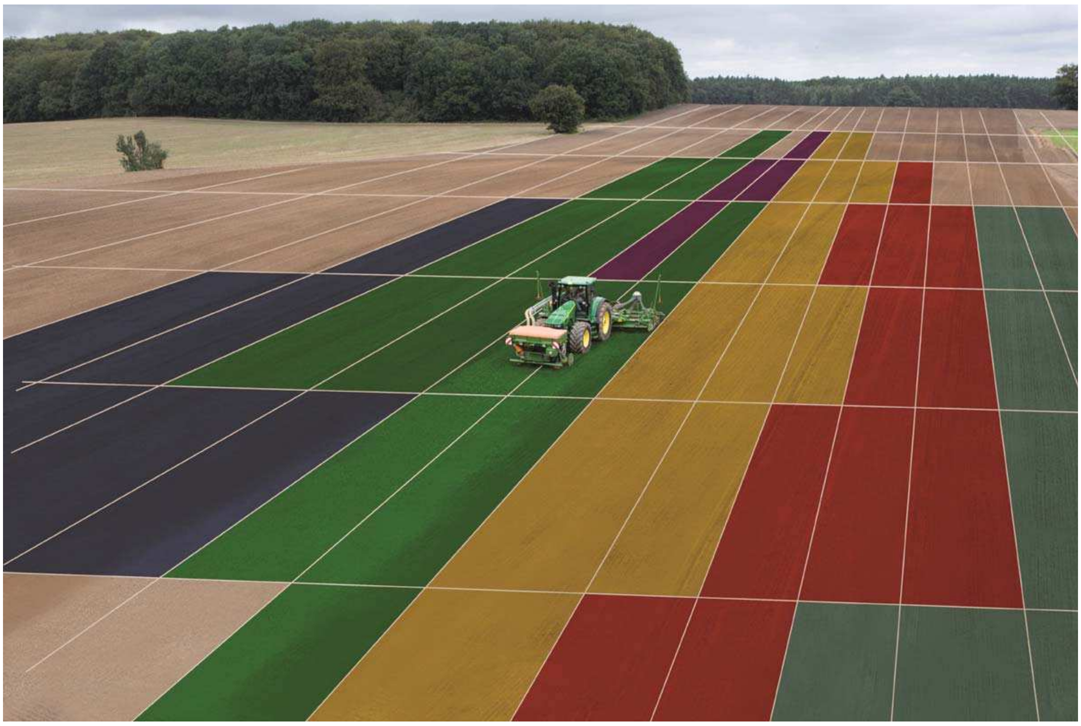
Figure 4. Sustainable phosphorus measures in agriculture—interventions in fertilizer selection and use, crop selection and soil management.



On the demand side, agricultural efficiency measures (AD1) that optimize fertilizer use include: appropriate fertilizer placement (AD1.1) ideally subsurface in the root area of the soil because phosphorus is not very mobile and adsorbs quickly to other compounds present in the soil rendering it inaccessible to plant roots [1,40,44]. Patchy spreading can therefore result in some areas of the field over-fertilized or under-fertilized [44]. Appropriate fertilizer timing (AD1.2) to match the season of plant root growth is also crucial, such as the use of slow and control-release fertilizers [49]. Appropriate application rate (kg/ha of P) of fertilizers (AD1.3) can also ensure soils are not being over- or under-fertilized for the crop and soil requirements. High or low-tech approaches such as precision agriculture (Figure 5), including variable rate application of phosphorus based on integrated geospatial technologies, yield and soil testing (AD1.4), can better ensure local soil fertility needs are met. One such precision agriculture company in Australia claims that this process can save up to AU$48/ha in phosphorus inputs [54].

To avoid permanent loss of phosphorus from the soil stock via wind, water or tillage erosion, a range of erosion reduction measures (AD1.5) can be employed, such as establishing cover crops, minimizing tillage, maintaining root-soil structure, mulching and establishing buffer strips [44,47]. While measuring erosion and other non-point losses may be difficult to calculate, such measures can be relatively straight forward and have been reported to significantly reduce erosion losses in the order of 40%–90% [44]. Other efficiency measures such as the addition of microbial inoculants (AD1.6) (e.g., Mycorrhizae fungi) to the root zone is said to increase the uptake of nutrients [47].

Figure 5. Precision farming through efficiently matching fertilizer application with actual soil nutrient needs. The colour indicates soil nutrient demand based on satellite and other data from field sensors and farmer knowledge (Image from John Deere/Land-Data Eurosoft).



Improving or maintaining soil quality is also a crucial measure to reduce the phosphorus demand in agriculture whilst maintaining productivity. Phosphorus readily bonds to aluminum, iron, calcium compounds or organic matter, rendering it temporarily unavailable to plant roots [1]. Soil acidity and other characteristics can affect the strength of these bonds, hence improving chemical and physical properties of soil (AD2.2) (such as pH, moisture, aeration, root-penetrability) can greatly increase availability of existing soil phosphorus to plant roots [18,49].

Phosphorus demand in agriculture could also be reduced in the long-term by reconsidering the profile of the agricultural sector—including exports—to favour the production of low phosphorus-demanding crops (AD2.1). This could range from switching crop types (e.g., rice, wheat, maize), breeding specific P-efficient species such as native varieties or gene selection [55]. Gamuyao *et al.* [56] recently identified the first phosphorus-efficiency gene in rice, which increases grain yield on phosphorus deficient soils by enabling early root growth for increased access to soil phosphorus.

These measures can all minimize the need for external phosphorus application, maximize productive uptake of phosphorus by plant roots and/or reduce losses to other land or water [55,57]. It is important however that appropriate measures are sought for the specific conditions. Detailed examples of phosphorus use efficiency in the agricultural sector can be found in Schroder *et al.* [44]

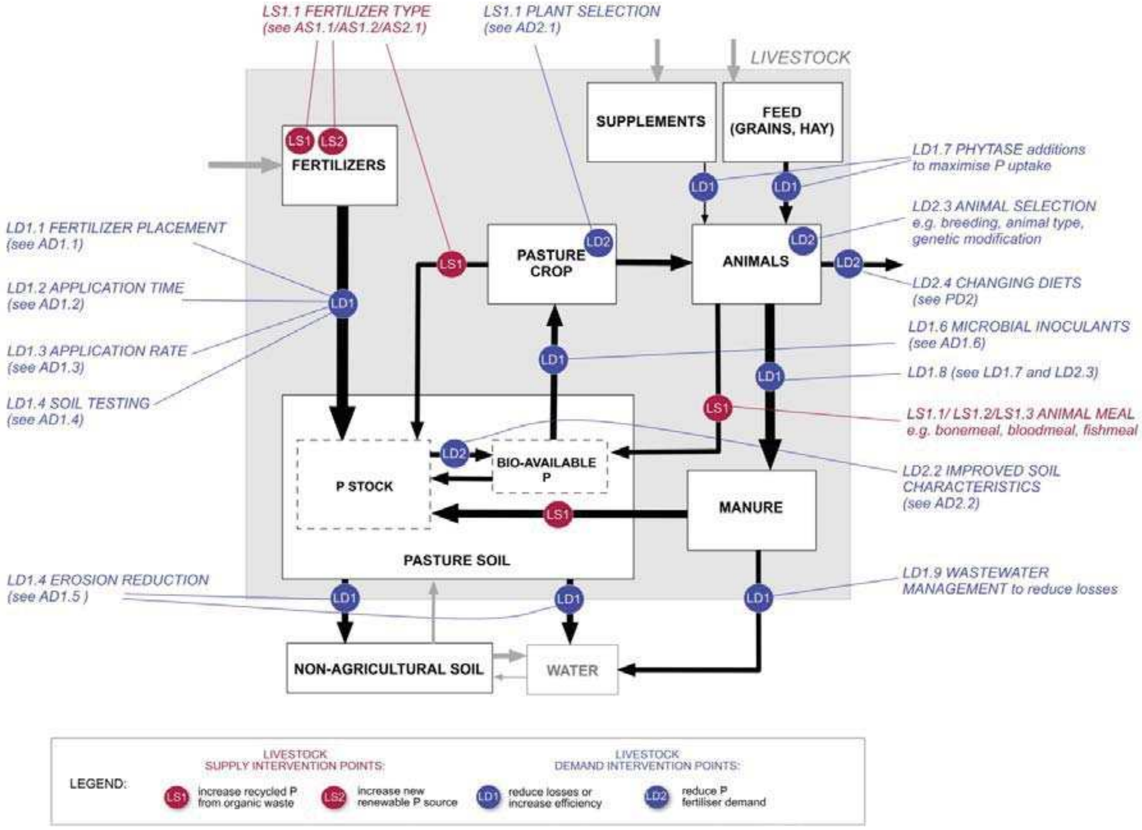
from a European perspective, Simpson *et al.* [58], Weaver & Wong [59], McLaughlin [60] and McIvor *et al.* [61] for an Australian perspective, and Smaling [45,62] for a Sub-Saharan African context.

3.4. Livestock Sector

The livestock sector accounts for a substantial portion of global phosphorus demand, via animal feed, fertilizer applied to pastures and mineral feed supplements [16]. While the rearing and consumption of livestock has contributed to local livelihoods and protein intake of billions of people over the past millennia, concerns about growing global trend towards more meat and dairy-based diets, especially those based on intensive practices, and the associated consumption of water, energy, nitrogen and phosphorus is raising concerns about the sustainability of the sector [63,64]. Further, from a phosphorus perspective, the conversion of crops to animal protein is particularly inefficient because the vast majority of the phosphorus entering the livestock sector ends up in the manure, bones and blood of animals rather than the edible components. Unless these components are captured and recovered for their phosphorus value, this can lead to substantial phosphorus losses to the environment (water and non-agricultural soils).

As for the agricultural sector, there are numerous sustainable phosphorus use measures in the livestock sector that can substantially reduce the overall demand for phosphorus, while maintaining productivity, reducing deleterious environmental impacts, animal welfare and supporting farmer livelihoods. Figure 6 indicates 19 such supply or demand measures.

Figure 6. Sustainable phosphorus measures in the livestock sector—interventions in animal selection, fertilizer selection and application, soil management and plant management.



In addition to those sustainable measures outlined in Section 3.3 Agriculture Sector that can similarly increase the phosphorus use efficiency associated with the use of fertilizers on pastures, pasture crop selection and improved pasture soil quality (that is, AD1.1–AD1.6; AD2.1, AD2.2), demand-side interventions in the livestock sector can include reducing phosphorus requirements in feed supplements (LD1.7). Non-ruminants such as pigs and poultry cannot readily absorb the phosphorus in feed (phytate) and hence mineral phosphorus supplements are added to livestock diets, which globally accounts for over 1 million tonnes of P per year (or 7% of global phosphorus demand) [26]. Much of this phosphorus is excreted in livestock manure. This phosphorus supplement intake (and associated high-phosphorus content in manure) can be reduced through the use of artificial enzymes such as phytase in feed which can increase the availability of phosphorus in feed to such animals [65].

Animal selection or breeding (LD2.3) can also minimize phosphorus demand. For example, University of Guelph scientists developed the first "Enviropig" which has been genetically modified to utilize phosphorus more efficiently. That is, unlike natural non-ruminants, the Enviropig can digest phytate, the main form of phosphorus in animal feed [66]. This has a significant phosphorus benefit of reducing the need for the addition of mineral phosphorus supplements to feed and simultaneously reducing the amount of phosphorus in manure which can pollute the environment. Further, this means the N:P ratio of the Enviropig's manure would be more appropriate to crop requirements. However adverse health consequences associated with the introduction of a genetically modified pig into the food chain are unclear and under investigation [67].

On the supply side, in addition to sustainable phosphorus supply measures identified in Section 3.3 (AS1.1, AS1.2, AS2.1) that relate to pasture fertilizer type, productive use of manures and farmyard organic material can serve as fertilizer supplements (LS2). The available manure will need to be more productively (and efficiently) recovered and reused for its phosphorus (and other nutrient) value. This means a high recovery rate, and transporting and reusing nutrients where they are needed, rather than spreading manure for disposal purposes. New technologies are emerging that extract and concentrate the phosphorus in bulky manures and other animal wastes (LD1.9), such as through struvite (struvite is magnesium ammonium phosphate in crystal form and high in phosphorus at 13%–14% P) precipitation or incinerator ash. In addition to reducing the pollution load on water bodies, this can have substantial benefits in countries where potential transport distances may be great.

Animal manure has always been widely used as a source of fertilizer in most regions of the world and indeed accounts for some 7 million tonnes of phosphorus each year [16]. However there are substantial geospatial imbalances both at the global scale, where in some parts of the world manure supply exceeds demand (e.g., North America, The Netherlands), while in other regions demand exceeds supply (e.g., Australia, Africa). On a local scale, soils tend to accumulate phosphorus in intensive livestock farms which generate a high rate of manure and are typically separated from cropping systems which demand phosphorus [68].

The phosphorus concentration of manures varies from 1.3% P in poultry manure to 0.04% P in cattle dung [47]. Livestock manures can also be mixed and composted with other solid farm organic matter such as bedding (known as Farm Yard Manure), food waste and human excreta. The resultant compost also has good soil conditioning properties that does not occur with direct application of organic wastes.

Other sources of phosphorus include the use of bonemeal (LS1.2), bloodmeal (LS1.3) and fishmeal (LS1.4), which all have high phosphorus concentrations. Phosphorus can be readily recovered from bones via low tech, low-cost means such as the "phosphito" process which converts the bones to high-concentrate soluble phosphorus through incineration with KOH and crop residues [69].

Other sustainable measures to reduce phosphorus demand in the livestock sector include changing diets to reduce global meat consumption and hence the substantial phosphorus footprint associated with the livestock sector (see discussion in Section 3.5 below).

3.5. Food Production and Consumption Sector

For the purpose of this paper, this sector includes all food processing stages from harvest to final consumption. That is, the food production sector begins with processing of harvested crops, animal products or slaughtered animals for processing into food and fiber, food distribution and wholesaling, food retailing and ends with food consumption. While often overlooked from a sustainable phosphorus use perspective [30], the food production and consumption sector presents numerous intervention points for implementing sustainable phosphorus measures. Sustainable phosphorus measures in this sector can not only reduce phosphorus consumption, but also avoid energy, water and other resource consumption, in addition to reducing solid waste generation and associated costs and greenhouse gas generation [70].

Compared to pre-industrial food systems, which were more local and smaller in terms of anthropogenic phosphorus flows, today's globalized food commodity chain has resulted in more players, more processes, further distances and increased trade of commodities. While this has increased food safety, access and variety, longer production chains contribute to more food losses in transport, production, storage and retail [70]. Globally, around 2 million tonnes of phosphorus per year in post-harvest and food waste is currently lost and not recirculated—that is, approximately 40%–50% of phosphorus is lost between farm and fork [3,16]. In developed countries, the majority of this waste occurs further down the chain during retailing and consumption [71]. For example, British householders alone discard £10 billion worth of food (equal to a third of the food that is purchased). Approximately 60% of this is food waste is unused edible food and hence avoidable waste [72]. In developing countries, the majority of the waste occurs due to spoilage, spillage and other losses upstream during food processing, transport and storage [71].

In the food production, processing and retailing sector, sustainable phosphorus measures equally focus either on demand, by reducing avoidable phosphorus losses in organic and food waste (PD1) such as reducing spillages or wastage of edible food, or supply by seeking to compost and reuse the phosphorus in unavoidable waste (PS1) such as banana peels and oil press cake waste [21]. Food waste constitutes organic waste from both food processing waste and prepared food waste associated with retailing and consumption. All forms can potentially be recovered for their phosphorus value (PS1.1), however they have different phosphorus concentrations. For example, the residual byproduct "oil cakes" following oil extraction from oilseeds contain at least 0.4-1.3% P which is significantly higher than crop residues 0.04%–0.33% P [47], while bonemeal contains 8.7%–10.9% P. The UN's Food & Agricultural Organisation [47] and Table 1 in Cordell *et al.* [24] lists phosphorus concentrations of organic waste. In the domestic setting, composting unavoidable waste (including both kitchen and garden and other organic matter around the house) can enable phosphorus in organic matter to be recovered for reuse locally (PS1.2) [73].

Organic waste can be avoided in the first place during food processing by reducing production losses and wastage (PD1.1). Producing food closer to the point of demand (PD1.2)—mostly from cities—would reduce food waste as well as energy, water and other resources. Ongoing urban and peri-urban agriculture (e.g., growing food on roofs, vacant land, gardens, public spaces, agroparks) in addition to vertical farms are all examples of more sustainable food production systems [74].

Food consumers (the final end users of most phosphorus) can collectively contribute to increased phosphorus use efficiency in the food chain (PD1.3), through measures such as improved food planning and shopping to reduce wastage (e.g., spoilage), use of leftovers, and avoid disposal of edible foods (even if their stated used by date has passed) [70,75]. Governmental and community campaigns such as "Love Food, Hate Waste" in UK and Australia (http://www.lovefoodhatewaste.com [76] and http://www.lovefoodhatewaste.nsw.gov.au [77] respectively) aim to tackle food waste minimization.

There is also a need for affluent societies to confront diets and shift towards less resource-intensive diets lower down the food chain. Changing diets in this context refers to influencing consumer preferences away from both phosphorus-intensive diets (PD2.1) and overconsumption (PD2.2). While growing children and pregnant women require a higher daily phosphorus intake, adults in developed countries generally consume greater than the recommended daily intake. Further, there is increasing evidence that excessive phosphorus intake can increase cardiovascular disease risk [78]. Nutritional or food security means ensuring healthy bodies and access to sufficient food for the more than 900 million people today who are undernourished [79]. Further, there are currently more overweight people than undernourished in the world [70,80]). It is estimated approximately 30% of cereals are used for cattle feed globally [64]. This figure is 60% for the EU. Meat and dairy-based diets require up to three times as much phosphorus as a vegetarian diet, in addition to requiring substantially more water, energy and nitrogen [3,81]. FAO predicts a doubling of global meat, dairy and fish consumption by 2050 (particularly in the rapidly developing world) [82]. A deliberate reversal of the current trend (in addition to a reduction of the already high meat demand in the developed world) could therefore significantly reduce the global demand for phosphorus in addition to other environmental impacts. Smil [83] calls for a "smart vegetarian" diet that prioritizes lower phosphorus-intensive foods, while the Food Ethics Council is encouraging supermarkets to reduce consumer choice and availability of environmentally damaging goods (including meat products) [84].

Many people in the developing world suffering from malnutrition or other chronic diseases such as cholera or diarrhea cannot fully absorb the nutrients they consume in food (such as phosphorus) [85]. Therefore, ensuring healthy bodies (PD2.3) can also increase phosphorus uptake and hence reduce overall demand.

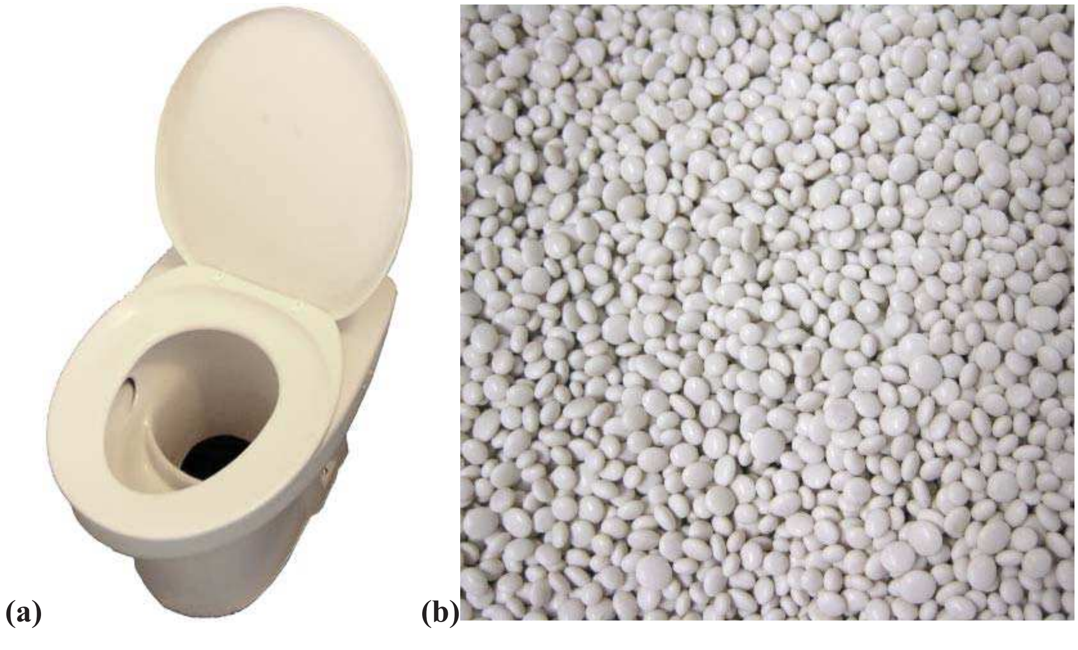
Finally, whilst representing a small fraction of phosphorus demand (approximately 2%–3%), the use of additives in foods, such as phosphoric acid (additive E338) to enhance flavor of beverages or moisture holding capacity in meats and seafood [86], could be minimized (PD2.4) to reduce the total demand of phosphorus and reduce cardiovascular risk.

3.6. The Wastewater and Sanitation Sector

For the purpose of this paper, the wastewater and sanitation sector includes all phosphorus-containing good and processes ranging from industrial wastewater to excreta via open defecation. This spans urban and rural settings, decentralized and centralized collection systems and treated and untreated waste. Humans produce approximately 1–1.5 g P/person/day in human excreta [53]. This means globally, the human population produces around 3 million tonnes of P in excreta alone. Approximately 10% is currently returned to agriculture as sludge or direct wastewater reuse [3]. This means on average approximately 90% ends up in the world's rivers, lakes oceans or non-agricultural land each year. Increasing the recovery of phosphorus from excreta and wastewater can not only generate renewable fertilizers, but also reduce the nutrient pollution load on receiving waterways (hence reducing eutrophication and algal blooms) [87], improve wastewater treatment process and maintenance [14] and increase farmer fertilizer security through local reuse [88].

Indeed, any wastewater/excreta fraction (such as urine, faeces, greywater, mixed wastewater), can be recovered through essentially any low- or high-tech means (such as direct reuse, mixing, compost, incineration, precipitation) at any scale (onsite, decentralized or centralized). Figure 7 indicates two examples. The most appropriate means and sources to target will differ from context to context and depend on a number of factors including existing infrastructure, cultural preferences, life-cycle energy, land use and demographics and logistics. Cordell *et al.* [24] set out an eight-step integrated framework to guide decision-making for phosphorus recovery and reuse.

Figure 7. Examples of phosphorus recovery in the wastewater sector (WS1): (**a**) onsite, low-tech, urine-diverting composting toilet, (**b**) struvite recovered from high-tech crystalisation of mixed wastewater (Photo source: Dana Cordell).



Globally, there are now more people living in high-density urban areas than rural areas [89]. This means cities are essentially "phosphorus hotspots" from excreta (and food waste) which presents both a challenge in terms of more concentrated nutrient pollution of waterways and an opportunity to capture the valuable nutrients in this waste stream for reuse in horticultural fields in peri-urban areas [3,90]. Indeed, urine is the largest single source of phosphorus emerging from cities [91]. Water and sanitation service providers will need to treat and manage sewage in a way that facilitates both the efficient recovery and reuse of nutrients through energy-efficient and cost-effective means [24].

There are trade-offs between recovering phosphorus at source and at a wastewater treatment plant. Capturing urine (WS1.1), faeces (WS1.2) and greywater (WS1.3) at their source (such as the toilet) can in some instances be much more energy-efficient and cost-effective than removing phosphorus at the wastewater treatment plant because extensive and costly sewage infrastructure is avoided [24]. This also avoids mixing such fractions with heavy metals (like Cadmium) found in industrial wastewater [92].

Ancient civilizations, particularly in Asia, commonly reused human excreta as fertilizer [93]. Urine can be used directly as a fertilizer because it is essentially sterile and contains plant available nutrients (N, P, K), while faecal matter can be safely composted and reused for its fertilizer and soil conditioning properties [94]. While most pharmaceutical residues and endocrine disruptors end up in urine, studies have shown that adverse health effects are low if the rate of urine application to agricultural soils does not exceed plant needs [95]. Drangert [96] estimated that the urine from one person alone provides more than half the per capita phosphorus required to fertilize cereal crops. Despite this, urine's potential as a fertilizer has been often overlooked in many modern societies. Documented cases of small-scale decentralized phosphorus recovery systems from around the world include in Zimbabwe [97], Burkina Faso [98], Vietnam [99], Germany [100], Sweden [101] and in developing countries in general [102]. While small-scale local reuse of human excreta has numerous benefits, in some instances the application will be limited, for example: if large transport distances are required (due to the low phosphorus concentrations—for example of urine has 0.07% P [103], in high-density built up areas where space for onsite systems are limited, and the transferal of management and maintenance responsibility to the householder or other local stakeholder [24].

At the centralized or large scale, phosphorus can be recovered in many forms from wastewater. Indeed, in developing countries there are as many as 200 million (mostly poor) farmers who frequently divert untreated mixed wastewater from cities for direct use in agricultural fields (WS1.4) because it is a cheap and reliable source of water and nutrients [104]. Further, it is estimated that two thirds of farmed fish globally are fertilized by wastewater [105]. Regardless of geography, it is essential that minimum precautionary measures are adhered to in order to avert serious health risks and the World Health Organization has now published extensive risk-based guidelines on the safe reuse of human excreta in agriculture and aquaculture [106].

The reuse of phosphorus via treated effluent from wastewater treatment plants is also practiced in many parts of the world (WS1.5). Mixed wastewater also contains phosphorus from greywater and other industrial wastes (predominantly detergents) in addition to human excreta. The reuse of the solid byproduct from wastewater treatment—sludge or "biosolids" is also frequently reused, however there are concerns regarding the presence of heavy metals, hence the importance of appropriate application rates (WS1.7). In the EU, phosphorus recovery rates from municipal wastewater via sludge reuse and other processes are currently 25% [107]. Activated sewage sludge contains approximately 1.4% P [47]. Incinerated sewage sludge ash (containing approximately 3.5% P) is also reused for both industrial phosphorus applications and for its fertilizer value (WS1.8). A Dutch sewage sludge treatment company recovered phosphorus from 30% of The Netherlands sewage sludge in this way and sold the product to an international phosphate producer for further refinement and use [108]. More recently, interest in recovering phosphorus via struvite crystallization of effluent streams (WS1.6) has increased [109]. Although struvite recovery processes commonly requires dosing of magnesium, advantages of the process include the production of a high concentrate (13%–14% P) with pure and consistent formula (monoammonium phosphate), that can be therefore transported further distances and applied as a slow-release fertilizer [110,111]. Shua *et al.* [112] argue that struvite recovery can also be more cost effective than chemical and biological removal.

Demand measures (WD1) which could reduce permanent phosphorus losses (and prevent pollution) and hence maximize phosphorus available for recovery include: reducing leakage of treated or untreated wastewater through repairing or avoiding cracked pipes (WD1.1), minimizing sewer overflows (WD1.2) or increasing soil holding capacity to reduce sub-soil phosphorus infiltration to water (WD1.3) or reduce dumping of biosolid into water bodies (WD1.4) and reduce spreading of biosolids on non-agricultural lands (WD1.5) to maximize the amount of phosphorus available for food production.

4. Developing Integrated Sustainable Phosphorus Options

The measures described in Section 3 are designed to increase the effective supply of phosphorus or to decrease the effective demand for phosphorus, thus improving the overall supply-demand balance. The impact of such measures on the supply-demand balance could, in principle, be assessed, allowing comparative analysis between them. However, implementation of these measures usually requires the action of a range of stakeholders and policy instruments, particularly to overcome institutional barriers and market failures that inhibit their uptake.

The analysis of barriers to the uptake of resource efficiency measures, and the policy tools, or instruments that are needed to overcome those barriers can be generalized across a range of resource issues. Previous research in this aspect has been undertaken by researchers in the water [113] and energy [114] sectors. A useful categorization of the barriers and associated policy tools includes:

- *Regulatory* instruments, such as targets (e.g., recovery of phosphorus from excreta or manure, *etc.*); limits (e.g., discharge limits on phosphorus to sensitive waterways) or bans;
- *Economic* instruments such as taxes (e.g., phosphorus tax) or trading schemes (e.g., phosphorus trading scheme in a catchment);
- *Communicative* or educational instruments such as stakeholder engagement processes and outreach (e.g., workshops, seminars); developing stakeholder-specific resource material.

Figure 8 depicts these policy tools on a policy palette as either primary instruments (in the primary colours red, blue and yellow) or secondary instruments (orange, purple and green) [114]. Examples of phosphorus options, comprising the measures plus the associated instrument, are shown as annotations on the graphic. The role of co-ordination is important as it combines the full range of instruments, and in the case of phosphorus is conspicuously absent in terms of the lack of institutional oversight of the issue of phosphorus scarcity [11].

Combining the measures outlined in Section 3, with a selection of appropriate policy tools or instruments, in Figure 8 yields options that can be not only assessed in terms of their phosphorus impact (kt P yielded or saved), but can also be assessed for their cost of implementation. A useful metric for comparison of the relative cost-effectiveness of these options is the unit cost, or levelised cost expressed, for example as $ per ton of P per annum ($/kt/a of P). Figure 9 provides an indicative graphical representation of this in terms of a "supply curve of saved or supplied P", showing a sample of the measures described in Section 3, combined with policy instruments to create options.

Figure 8. The policy palette, indicating seven policy instruments embedded within society/culture and requiring co-ordination across instruments. Phosphorus-related examples are also indicated (adapted from [114]).

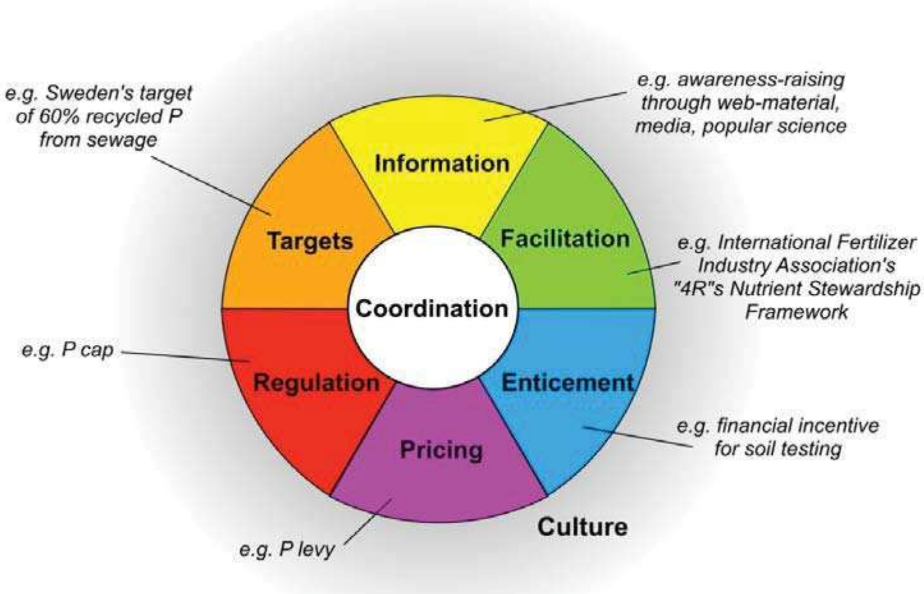
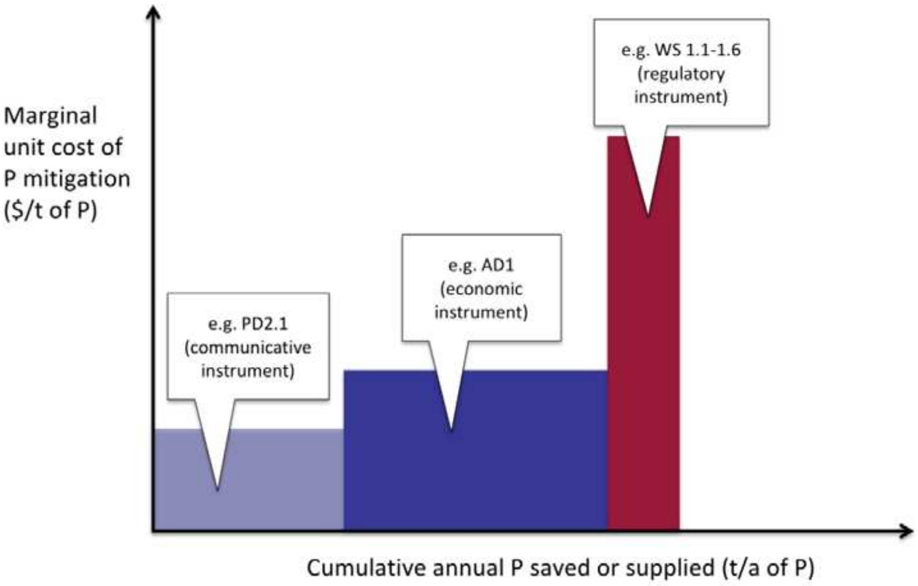


Figure 9. An indicative "supply curve of saved or supplied P" using some of the measures in Section 3. The ranking is illustrative only.



The process of identifying the unit cost of options, is part of a decision-making framework determining the best portfolio of options for implementation. The water and energy sectors provide such a framework in terms of integrated resource planning, as described by Turner *et al.* [115] and White *et al.* [113].

The overall framework, adapted to the case of phosphorus would include:

1. Identify objectives and drivers, by seeking agreement amongst the key stakeholder regarding the key drivers and objectives, as these will influence the most suitable measures (e.g., pollution prevention, desire for renewable phosphorus fertilizers, farmer productivity) [24].
2. Identify a baseline, or Business-as-Usual demand trajectory, sometimes called a reference case, which can explicitly show targets, and from which the impact of options can be compared [21].
3. Identify and categorise the most comprehensive range of measures that could meet the objectives, and assess the P savings or yield associated with the measures.
4. Match the measures with appropriate policy instruments, using the policy palette described in Figure 8, and with reference to stakeholder roles and responsibilities [11,116,117].
5. Estimate the annual amount of phosphorus saved (e.g., in "negatonnes per annum" in the case of efficiency options) or supplied (in the case of recycling options) for the selected options and represent these graphically in a "supply curve" (such as Figure 9).
6. Based on the cost-effectiveness of options, construct a realistic and achievable portfolio of options for implementation, based on the complementarity of different options, and taking into account other parameters beyond unit cost, such as risk, environmental impact or benefit, or even spread across sectors.

Such an informed decision-making framework can guide the most effective and sustainable phosphorus investment strategy for a given region or country, rather than risk investment in inappropriate options that may not meet set targets or goals of phosphorus security. Implementing options requires political will, and in many cases investment by public or private sources. Policy makers at the national or local government levels will play an important role in securing a sustainable phosphorus future through such measures as:

- initiating dialogue and consensus building between stakeholders;
- Facilitating or initiating a coordinated response to phosphorus scarcity, including independent research;
- Identifying key national policy priorities;
- Embedding knowledge of phosphorus sustainability issues into relevant educational curriculum, including practical aspects such as school garden that may be fertilized from organic waste produced from urine-diverting toilets and/or food and landscape waste compost.

5. Conclusions

This paper has provided a comprehensive and integrated classification of potential sustainable phosphorus measures that can be implemented to mitigate or adapt to the global challenge of phosphorus scarcity. Numerous opportunities exist for supply and demand measures at different intervention points throughout the food system—and even within a single sector—e.g., this paper has identified 19 intervention points in the livestock sector alone. This framework highlights the importance of taking a systems approach in order to: firstly, seek most appropriate (cost-effective) measure for context; secondly, ensure together these meet phosphorus and food needs; thirdly to ensure synergies and conflicts are addressed, and lastly to ensure the entire sub-system related to a specific intervention is addressed, for example, when phosphorus is recovered from one sector, transport and logistics and bioavailability and farmer acceptability are all considered. Finally, a new decision-making framework has been introduced to help identify the most cost-effective measures for a given context and which policy instruments are most appropriate to facilitate such measures.

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