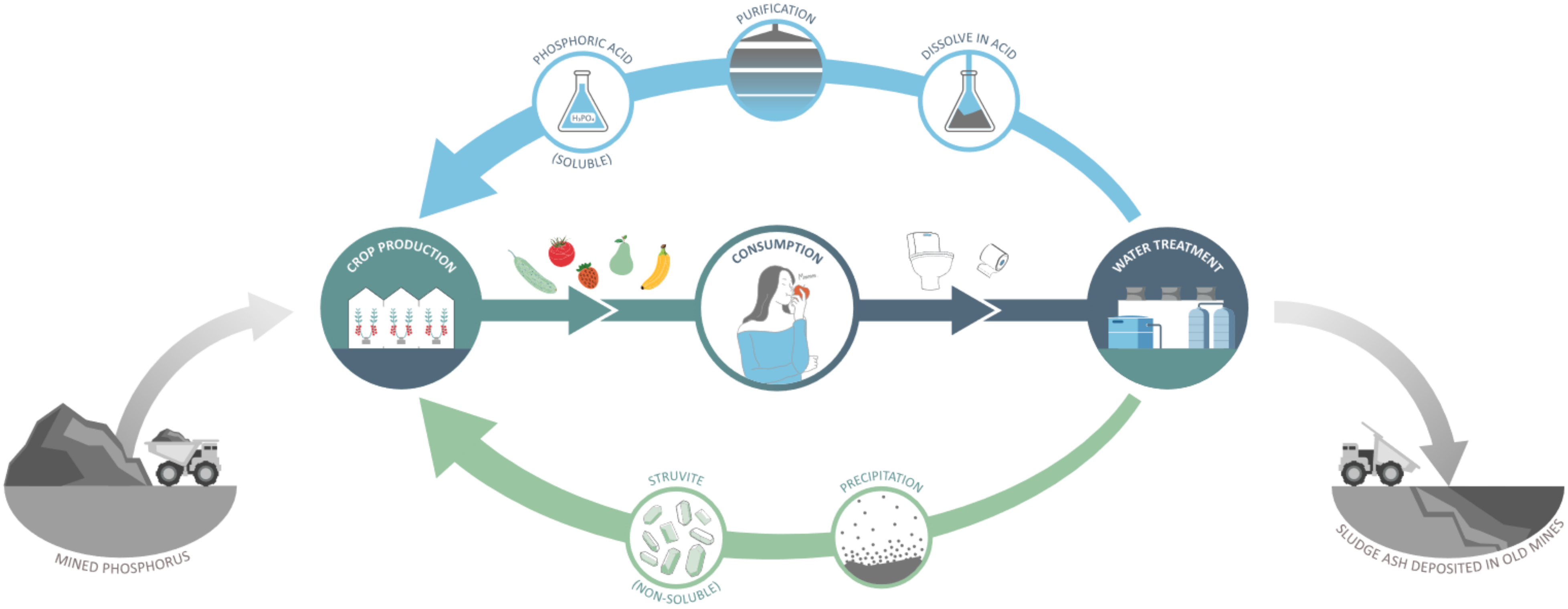
Phosphorus Recovery from Side-Streams for Horticulture



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Introduction

The Netherlands has established a strong position in producing and exporting safe and high-quality agricultural products by focusing on innovation and high efficiency. However, urgent challenges need to be addressed, such as reducing nutrient emissions from the agrifood system and reducing dependence on mineral resources. To tackle these challenges, the agrifood system needs to transition from a 'linear' system towards a more 'circular' one. Such a transition requires changes in the behaviour of food producers, waste processors and consumers. In this circular system, nutrients from manure, industrial- and municipal waste and other side-streams are returned to the food production system as much as possible, while minimizing losses to the environment.

Figure 1: A picture of greenhouse horticulture.

Phosphorus fertiliser presents unique challenges due to its crucial role in crop growth. Like nitrogen, excessive phosphorus emissions are associated with environmental problems such as eutrophication. However, unlike nitrogen, mineral phosphorus has limited availability as it comes from finite deposits. The maximum global production rate of phosphorus, known as 'peak phosphorus', has been anticipated to happen between 2060 and 2100, after which phosphorus will be harder to extract and will become more expensive [2, 3]. Recent discoveries of new phosphate rock deposits in Norway may delay this, but P remains a finite resource. Competition for this resource will likely increase in the next decades, particularly due to its use in batteries. In addition, Dutch regulations mandate virtually zero P emissions from horticultural production in 2027 because of environmental concerns [5, 6]. This requires the precise management of nutrients during the crop production cycle, which makes greenhouse horticulture particularly reliant on pure (phosphorus) fertilisers.

In the Netherlands, a significant proportion of fruit and vegetable production takes place in greenhouses where the plants are grown in artificial growing media fed by a nutrient solution (referred to as soilless or fertigation systems) with highly controlled climate conditions and nutrient supply. Unlike open-field agriculture, greenhouse horticulture mainly relies on precisely formulated nutrient solutions, with minerals sourced from finite natural reserves. This white paper focuses on the circular potential of one of the key nutrient minerals: phosphorus (P). P presents unique challenges as its reserves are finite, and non-circular use may lead to irreparable loss of P and diminished food security for future generations.

Circular economy principles propose reusing P-rich side-streams in the agrifood system, with greenhouse horticulture potentially playing a key role. This white paper summarises a report published by WUR in 2024 [7] and discusses and evaluates the following:

1) available P-rich side-streams in the Netherlands;
2) current technologies to convert them into fertiliser products suitable for greenhouse cultivation;
3) the applicability of recovered P products in soilless horticulture; and
4) the associated contaminant risks.

Application of P in current fertigation systems

In fertigation systems, nutrients are automatically fed into the circulation water that feeds the roots of the standing crop (Figure 2). Two nutrient-containing tanks (A- and B-tank) are commonly used to separately store and deliver different types of nutrients or fertilisers. Each tank contains a set of nutrients or fertilisers that are compatible when mixed in one tank. Crucially, P must be stored in a different tank than calcium and iron, or else P-precipitates may form. Hence, calcium (Ca) and iron (Fe) fertilisers are stored in the A tank, and P-fertilisers in the B tank. During fertigation, the irrigation system draws water from a water source and mixes it with the appropriate amounts of fertilisers from the A- and B tanks before delivering the nutrient solution to the plants' roots. The excess not taken up by the crop, referred to as 'drain', is recaptured and reintroduced into the system. Fertigation allows for precise control and efficient nutrient delivery based on the crop's specific needs during the growth cycle.

It is crucial that the fertilisers used in soilless growing systems are fully soluble and do not form precipitates under typical concentrations and pH levels present in fertigation systems. This is a given for many compounds currently used, presented in Table 1.

Table 1. The names and chemical formulas of compounds used in synthetic fertilisers in greenhouse horticulture, adapted from Sonneveld, Voogt [8].

Name	Chemical formula	%P	Solubility	Used in fertigation
(Ortho)phosphoric acid	H_3PO_4	32	High[b]	Yes
Mono potassium phosphate	KH_2PO_4	22	High[b]	Yes
Mono ammonium phosphate	$NH_4H_2PO_4$	26	High[b]	Yes
Polyphosphate	$HO(HPO_3)_nH$	Trademarks[a]	High[b]	Yes
Super phosphate	$Ca(H_2PO_4)_2$	20	Low	No
Dicalcium phosphate	$CaHPO_4$	20	Low	No

[a] Exact chemical composition is not published

[b] Products with high solubility are sold in liquid and solid form, except for phosphoric acid, which is only sold as an aqueous solution.

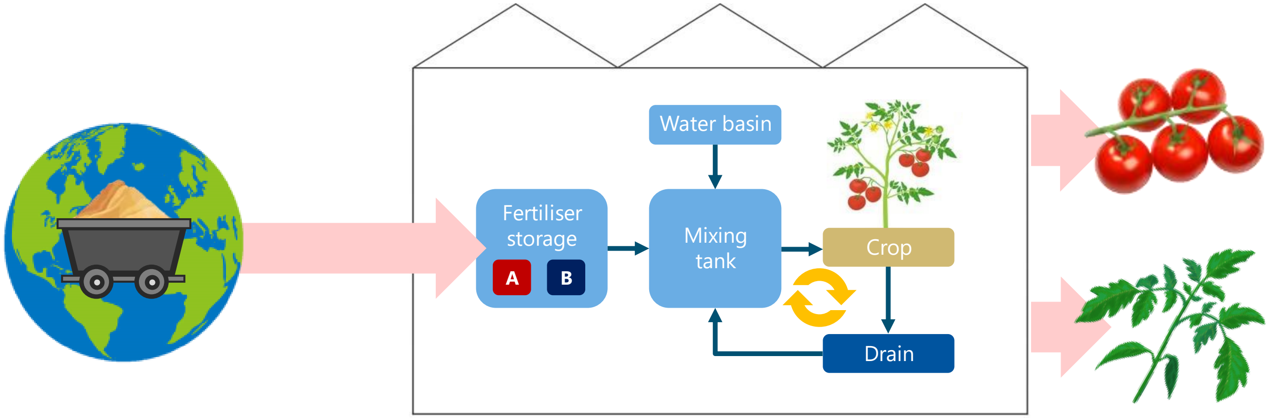

Figure 2. P application in a fertigation system using linear sources of nutrients

P-rich side-streams as a potential source of circular P

The total greenhouse area in the Netherlands is approximately 10 000 ha. Van der Lugt [9] estimates that greenhouse horticulture uses around 2 500 tonnes of P per year. Various organic side- and waste streams, including by-products from agrifood production and municipal wastewater treatment, provide sufficient P to serve the sector's demand as shown in Figure 3. The major P-rich side-streams include the following:

Manures. Manure emerges as the largest circular source of P, with differences in concentration and processing affecting its usability by altering its physical, chemical, and biological properties. While direct application of liquid manure to arable land is common, this is restricted by legal limits resulting in a manure surplus in the Netherlands. The affordability of P recovery varies with the manure type, with ruminant digestate being assessed as the most affordable option, but also that with the lowest concentration, making P recovery more challenging.

Sewage sludge. In the Netherlands, wastewater treatment plants process approximately 9000 tonnes of phosphorus annually, which is sufficient to meet the P demand of greenhouse horticulture. Sludge is dewatered and sometimes processed by anaerobic digestion to generate biogas. The dewatered sludge or digestate (in total 1.4 million tonnes) is incinerated into sewage sludge ash (SSA), where the majority of P ends up. It is technologically feasible to recover P from sewage water and sludge.

Ashes from manure and sludge. Several ashes resulting from the incineration of side-streams are a source of P. On top of sewage sludge ash, another particularly relevant source for the Netherlands is chicken manure from an annual production of 500 million broiler chickens. Approximately 30% of chicken manure is currently incinerated, leaving behind an ash rich in P and K that is often exported for use in fertiliser. Similarly, 95% of sewage sludge in the Netherlands is incinerated, generating sewage sludge ash (SSA) of approximately 10% P. Despite the benefits of incineration (mass reduction and pollutant elimination), SSA is mainly landfilled or used in construction, resulting in loss of precious P. Incineration plants have significant potential to produce P-fertilisers, thus retaining P within the nutrient cycle rather than allowing its loss through disposal practices. Efforts to recover P from SSA are gaining momentum due to legislative requirements, technological advancements, and environmental considerations. For instance, upcoming legislation in Germany mandates P recovery from sewage sludge (ashes), putting limitations on Dutch sludge exports to the country and mandating alternative routes for sludge processing.

Bone meal. About 10 000 t P per year is contained in bone meal, which is a by-product of animal carcasses or slaughterhouse waste. Two-thirds of Dutch bone meals are already utilized as an additive in ceramics or as a slow-release fertiliser because of its phosphorus content of 7-9%. Therefore, using bone meal as a P-source in greenhouse horticulture may not directly address the need for sustainable nutrient cycle closure, but rather redirect an existing closed loop.

Compost and Champost. Compost consists largely of composted fruit, vegetable, and garden waste (in Dutch, 'GFTe' waste: 'groenten, fruit, tuinafval & etensresten'), whereas champost is used as a mushroom substrate and consists of a mixture of horse manure, chicken manure, straw and gypsum. The spent champost is more or less depleted of N, but still contains some P. The P volumes of both composts are comparably small and both streams are already used as (fertilized) potting material or soil supplements. Moreover, they are costly per kg P and their added value lies not only in their mineral content but also in their organic matter content. The large volume in combination with low P content will compost and champost is unlikely to be considered a source of P fertilisers unless the CHO fraction is largely removed (converted into energy) by fermentation or incineration, leaving a P-rich ash.

These listed side-streams are mapped for suitability as potential P-source, based on three criteria: 1) the total annual amount of phosphorus; 2) the concentration of P; and 3) the anticipated price per kg P (Figure 3). In this figure, the total amount of P necessary in greenhouse horticulture is also shown.

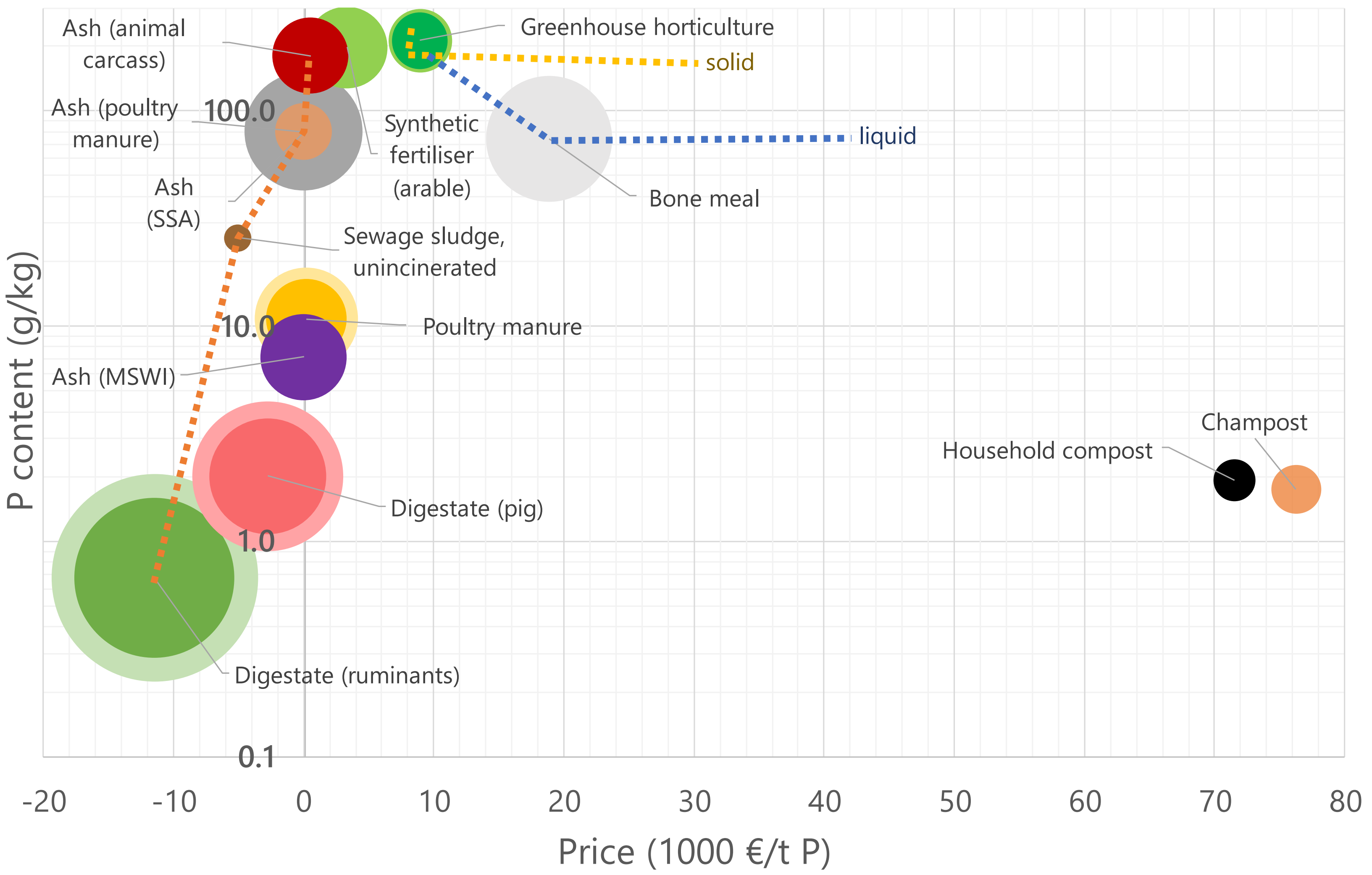

Figure 3. An overview of the major phosphorus-containing side-streams in the Netherlands. The horizontal axis shows the price (€/t P); the vertical axis (logarithmic) shows the P concentration (g P / kg). The sizes of the circles correspond to the total amount of P (ton) they represent. For manure, the lightly-coloured perimeter represents the organic fraction of phosphorus in the total flow. The dark green part of greenhouse horticulture represents the P demand (ton and current median price) of soilless systems. The yellow and blue dotted lines represent the range of possibilities for solid and liquid fertilisers respectively. An orange dotted line is added as a Pareto front.

Figure 3 shows a trade-off between P concentration and the price of side-streams. The Pareto front shows the side-streams for which it is impossible to improve in one criterion without sacrificing the other. For example, poultry manure is not on the Pareto front because other cheaper side-streams exist and have a higher P concentration. The possible side-streams on the Pareto front are ruminant digestate, unincinerated sewage sludge, sewage sludge ash, poultry manure and animal carcass ash. Compost and champost are deemed unsuitable as source material for P recovery due to their low P content and high costs.

Perhaps the most important observation from Figure 3 is the placement of the circles representing synthetic P fertiliser in arable farming and greenhouse horticulture. In the Netherlands, greenhouse horticulture uses one-third of the total synthetic P fertiliser, since arable farming also uses manure. Moreover, the price of this fertiliser is about three to ten times higher than in arable farming. Although greenhouse horticulture has stricter requirements, this may leave more economic room for products based on P recovery through novel technologies.

Side-stream price and concentration are the most relevant factors to consider, but not the only ones. One factor is the chemical or salt form in which the P is present, determining suitability for P recovery technologies. Other aspects include production scales and recovery costs of P recovery technologies. Another criterion that must be factored in when choosing side-streams is the presence of contaminants, which is not so much a cost-limiting factor, but rather introduces possible risks and non-compliance issues with fertilization law. These aspects are covered in separate sections, which cover technologies, intermediate products and contaminant issues.

Technologies to recover P from side-streams

Following the selection of P-rich sources, this section focuses on P recovery from manure, sewage sludge and ashes. This section presents the main P recovery technologies, focusing on processes that could be implemented in the short term. P recovery processes use feedstocks that can be classified into two groups: aqueous solutions (liquid fraction from manure, wastewater) and solid materials (sewage sludge, ashes, dewatered manure).

When P is dissolved in wastewater, it can be recovered or removed by using (a combination of) four principles: crystallization & precipitation, adsorption, biological removal and membrane separation processes (Figure 4). During biological removal, P is accumulated in microorganisms, which eventually end up in the solid phase (i.e. sewage sludge). With crystallization & precipitation, Ca, Mg or Fe-salts are added to the water to precipitate the dissolved P as Ca-P ($Ca_3(PO_4)_2$, $Ca(HPO_4)$ or $Ca(H_2PO_4)_2$), struvite ($(Mg(NH_4)PO_4 \cdot 6(H_2O))$ or vivianite ($(Fe_3(PO_4)_2 \cdot 8H_2O)$).

When P is present in the solid phase, thermochemical processes or wet-chemical processes are used (Figure 4). An example of a wet-chemical process is using an acid to mobilize P, which is commonly used to extract P from sewage sludge and SSA. After the extraction of P from solids, again (a combination of) three methods can be used to further purify P: precipitation/crystallization, affinity processes (i.e. adsorption, ion exchange) and membrane separation. Here we briefly discuss the methods used to recover P from manure, sludge, and sewage sludge ashes:

Manure. An example of a P recovery process from manure is the RePeat process [10] (Table 2). The following steps are used for P recovery from manure: anaerobic digestion of manure, separation of the digestate in solid and wet fractions, hygienisation of the solid fraction to kill microbes, acidification of the solid fraction to liberate P and finally recovery of a Mg-P or Ca-P precipitates by adding magnesium hydroxide (Mg(OH)2) or calcium hydroxide (Ca(OH)2). P recovery efficiency is generally high.

Sludge. Recovery of P from sludge is challenging due to low recovery efficiencies (35-70%); high costs; and the presence of a plethora of micropollutants, including human medicines, drugs, detergents, per- and poly-fluoroalkyl substances (PFASs) and heavy metals. P recovery from sewage sludge is already operating in the wastewater treatment plant of Amsterdam-West. Sewage sludge is first anaerobically digested. Then $Mg(OH)_2$ is added and the sludge aerated to start the Mg-P crystallization. The resulting struvite crystals are washed to remove contaminants. A commercial actor in the field of struvite production is Veolia, which has implemented its proprietary Struvia™ process [11] in various WWTPs in Europe and North America. A more or less similar approach, but using iron and the proprietary ViviMag® [12] process to precipitate P as vivianite, is planned to come into operation in 2025 at the Nieuwveer WWTP of Waterschap Brabantse Delta. To make the insoluble P locked in struvite or vivianite available, the P could be extracted again using an acid, and subsequently further purified to phosphoric acid (P-acid, H_3PO_4).

Ashes. Ashes result from burning organic wastes, such as animal carcasses, manure or sewage sludge. The resulting ash is free from microbes, organic matter and most organic micropollutants, but is rich in (heavy) metals [13]. The P content of ashes can be up to 15% and P can be recovered from ash with an efficiency of over 90%. A further advantage of starting from ashes is the possibility to produce P-acid, which can be used directly in soilless systems. P-acid is produced from ashes using wet chemical leaching, usually with an acid as a leaching agent. An advantage of using sulphuric acid or oxalic acid as a leaching agent is the simultaneous formation of insoluble gypsum or calcium oxalate to avoid the formation of calcium phosphate [14]. Other possible P products recovered from ashes are ammonium and calcium phosphates.

Table 2 gives an overview of the processes used to recover P from manure, sludge and ashes and the resulting P-products.

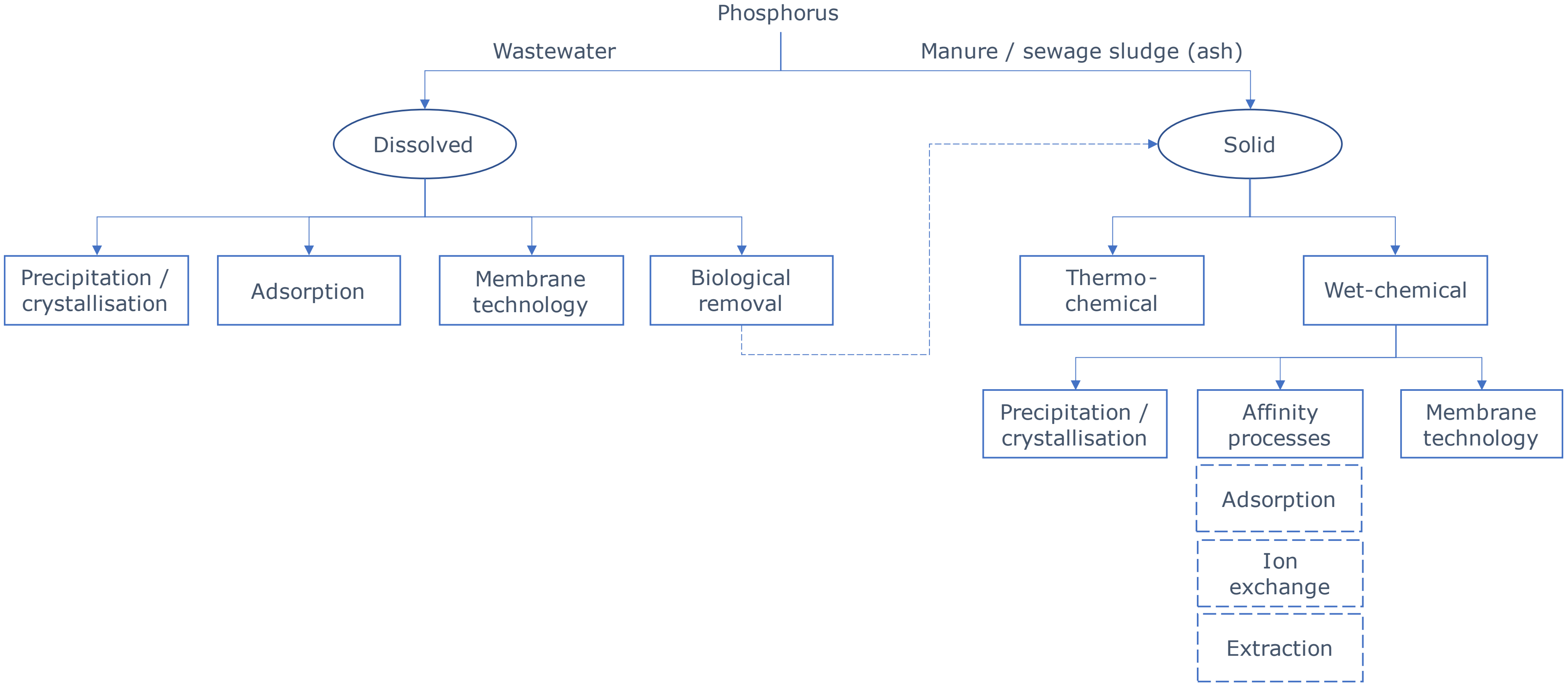

Figure 4. An overview of possible processes to recover phosphorus from different sources, categorised as liquid (where P is dissolved) or solid based on Witek-Krowiak, Gorazda [1].

Table 2. Overview of P recovery processes of companies to extract P from manure, sludge, and ashes.

Feedstock	Process	Main P-product	Raw materials	By-products
Manure	RePeat	Struvite (or Ca-P)	(Sulphuric) acid, magnesium hydroxide (or calcium hydroxide)	Soil conditioner
Sewage sludge	Struvia	Struvite	Magnesium chloride, co-substrate (carbon source) for bio-acidification	Biogas, organic fertiliser
	PULSE	Ca-P (or Mg-P)	(Hydrochloric) acid, metal extraction solvent, alkaline solution (regeneration extractant solvent), lime, calcium hydroxide	Sludge residue, metal solution, waste water
	EuPhoRe	De-mineralised ash	Magnesium chloride	Flue gas
Sewage Sludge ash	TetraPhos	P-acid	(P-acid), sulphuric acid, hydrochloric acid	Ash residue, gypsum, metal solution
	RubiPhos	P-acid, Ca-P, or struvite	Sulphuric acid	Ash residue, metal solution
	PARFORCE	P-acid	hydrochloric acid, regeneration agents (1st ion-exchange: hydrochloric acid or sodium thiosulfate; 2nd ion-exchange: hydrochloric acid or sulfuric acid H_2SO_4)	Ash residue, metal solutions, road salt
	Phos4Life	P-acid	Sulphuric acid, extraction solvent, regeneration chemicals	Ash residue, metal solution, (Ironchloride)
	SusPhos	Ammonium-P	Sulphuric acid, solvent, ammonia	Sand, metals, gypsum
	Ash2Phos	Ca-P	Hydrochloric acid, lime	Ash residue, metal solution, salts, iron chloride, sodium aluminate

Use of P recovered from side-streams in a fertigation system

As outlined already, several P recovery processes can produce phosphoric acid, which can be mixed into the current fertigation system's B tank. Other P recovery processes produce struvite, calcium phosphates or vivianite, which are not fully soluble in water under typical conditions.

If P recovery processes producing phosphoric acid are not cost-effective or cannot produce P-acid with the required purity, another option could be to apply struvite or Ca-P in adapted fertigation systems instead. This will require installing a third 'C' tank in which these products are dissolved in an acidic solution, and adjusting the fertigation strategy accordingly. Whether, and under which conditions, this is possible was analysed with OLI Studio Stream Analyzer software [15]. Our analysis shows that based on pH and nitric acid concentration, all four compounds can be fully dissolved in a C tank at a pH of approximately 3 (**Error! Reference source not found.**), resulting in technological opportunities to use these Ca-P or struvite as P fertiliser in a new fertigation system. Assuming nitric acid, this gives a ratio of nitrate (NO_3^-) to phosphorus in the C tank between 0.1 and 2.1, varying considerably between the four products.

The effects of the C tank on the recipe, taking other nutrients into account, are briefly described as follows. Monocalcium phosphate ($Ca(H_2PO_4)_2$) can be used in current fertigation systems without any change in the nutrient recipe. For di/tri Ca-P, the grower will have to choose between too much calcium or not enough nitrate for the crop, albeit with a difference of around 1 mmol l^{-1}. Alternatively, sulphuric acid can be added to the C-tank, to decrease the required amount of nitric acid and to reduce the NO_3^-:P ratio. The use of struvite results in slightly more magnesium and ammonium going to the crop compared to the current nutrient recipes, though this difference is relatively minor at 0.1-0.2 mmol l^{-1}.

Table 3. The results of the OLI simulation for a hypothetical 'C-tank' where P products are dissolved on-site in acid, with the product's concentration, the maximum pH required for it to fully dissolve, and the corresponding minimum concentrations of anions from the acid used. Products are given in descending order of N:P ratio.

Product	C-tank concentration (mmol l^{-1})	Maximum pH (precipitation point)	HNO_3^- concentration (mmol l^{-1})	NO_3^-:P ratio (-)
Tri Ca-P ($Ca_3(PO_4)_2$)	75	2.8	310	2.1
Struvite ($Mg(NH_4)PO_4 \cdot 6(H_2O)$)	150	3.3	300	2.0
Di Ca-P($Ca(HPO_4)$)	150	3.0	160	1.1
Mono Ca-P ($Ca(H_2PO_4)_2$)	75	3.2	10	0.1

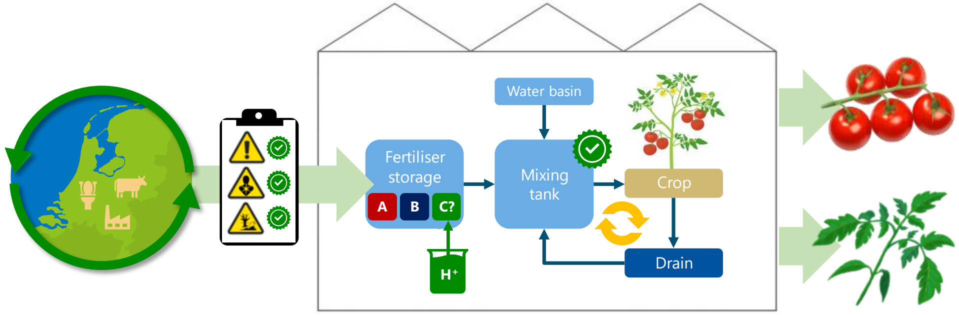

Figure 5. P-application in a circular fertigation system

Contaminants

The recovery of P from side-streams is important for a circular food system, but such a system could pose food safety hazards. Many chemicals used in crop and livestock protection (such as pesticides, Cu, Zn, and veterinary drugs) or in food production, waste treatment or nutrient recovery may end up as contaminants in the recovered products, such as a P-fertiliser. These contaminants may enter the agrifood system and potentially affect plant growth or compromise the safety of the consumable part of the crop. Figure 6 summarises the potential hazards in a circular agrifood system.

Recycled fertilisers may contain various contaminants, making it necessary to consider safety in the design phase of agricultural food production systems to ensure the safety of fertilisers for crops, consumers, and the environment. The European Fertilising Products Regulation (FPR) regulates the trade and transport of fertilizing products within the EU, aiming to promote circular agriculture while ensuring environmental and health safety. Member States must align their national fertiliser regulation – for the Netherlands, the Fertilization Act (FA) – with the new FPR. The FPR and FA set limits for organic contaminants, pathogens, heavy metals, and other inorganic contaminants to prevent accumulation in soil or recycling via crops that may compromise food safety.

The legislation covers organic contaminants such as heavy metals, polycyclic aromatic hydrocarbons, human pathogens, and mineral oils. However, the FPR currently lacks limits for pharmaceutical contaminants and persistent organic pollutants such as PFASs and dioxins in fertilisers, though future regulations may include them due to environmental concerns.

In addition to legislation, recirculating systems have unique challenges compared to open-field arable farms because contaminants introduced into a circular system remain within the system. Since fertilisers are recirculated through the system, contaminants may accumulate within the system, posing safety risks. Although heavy metals, such as cadmium and arsenic, could be within legal limits, they can still pose risks to crops and human health in such cases. Therefore, careful monitoring is necessary when creating a production concept that relies on recycled nutrients. Moreover, the sodium content of fertilisers in soilless systems must be as low as possible to ensure fertigation water quality throughout the crop cycle, ideally over 20 times lower than the current limit in the EU FPR.

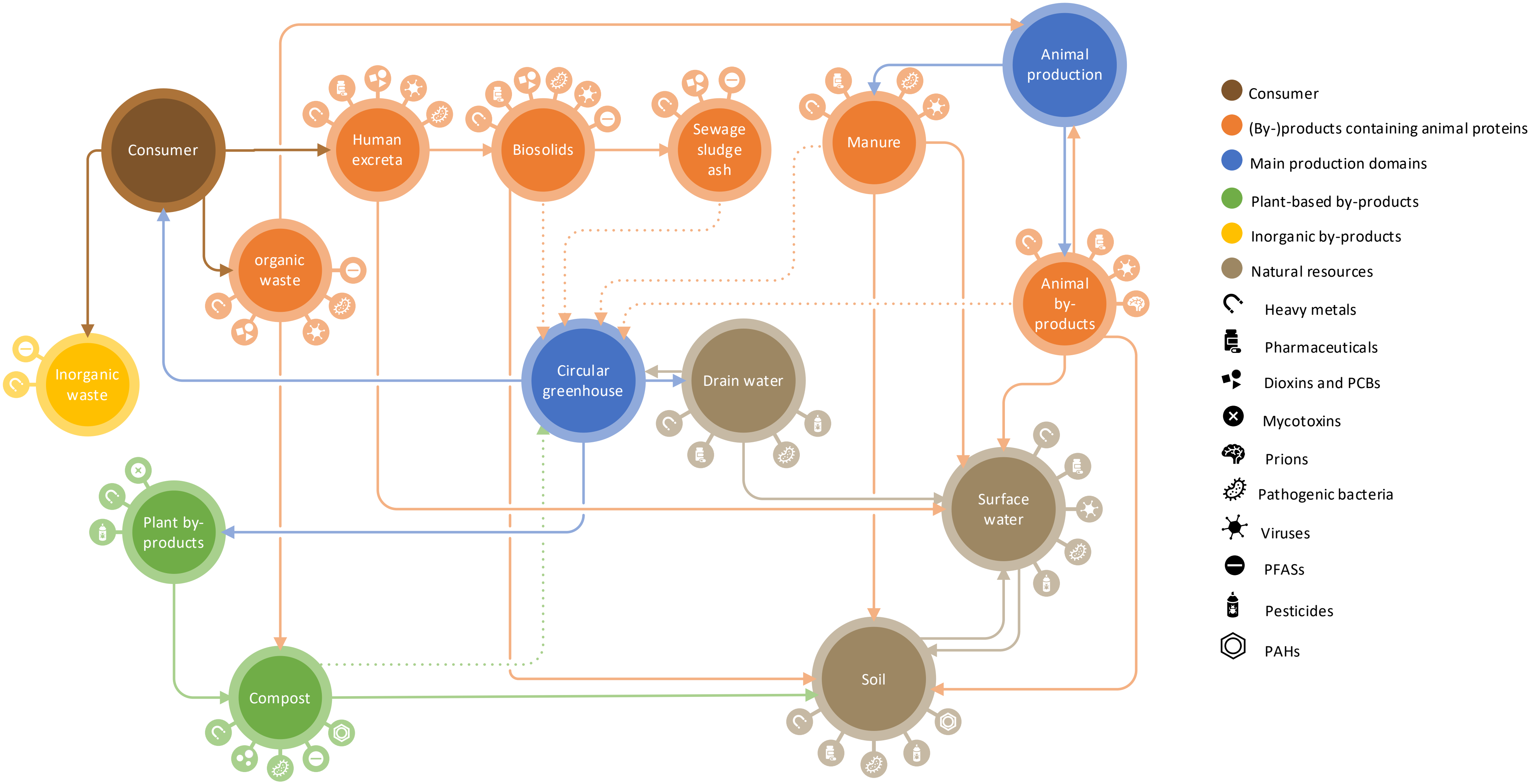

Figure 6. Potential (food) safety hazards in a circular greenhouse resulting from the recycling of side-streams, showing the potential sources and transmission routes into the greenhouse of possible microbial- and chemical contaminants and emissions into the environment (surface water, soil). Adapted from Focker, van Asselt [4].

Conclusion & future prospects

P is essential for plant growth and food production. However, mineral P sources are limited in availability. Recycling P in the agrifood system is therefore essential to ensure food security for future generations. Greenhouse horticulture is exceptionally efficient with its P, resulting in virtually no losses of P to the environment. Whilst this is both necessary and possible, it means fertilisers must meet specific requirements.

Various sources are promising for P recovery, particularly municipal sludge (ash) or chicken manure (ash). P can be recovered from municipal wastewater or manure as Ca-P or struvite. These products, whilst not directly soluble, can be dissolved in acid and mixed into the fertigation water via a third tank (C-tank). P recovered from sludge ashes can be recovered as P-acid or ammonium-P, which can be applied directly as a mineral fertiliser in the classic fertigation system consisting of an A and B tank. Recovery techniques starting from manure or sludge currently only produce struvite or Ca-P, therefore requiring a C tank.

Both P recovery routes are technically well-developed and are at the stage of industrial scale-up. Parties active in P extraction from by-products or waste/residual streams are developing market outlets for the recovered P. The horticultural sector is not necessarily the only possible customer, but it does have economic advantages, as products are on average more expensive when compared to arable farming. Therefore, we recommend that the greenhouse horticultural sector initiate its transition to the use of recycled P and enters into discussions with suppliers of recycled P to guarantee the supply of circular P for the future. The transition into a circular P use in horticulture should be supported by research on whether and how the new P-fertilisers can be best integrated into fertigation systems, especially since fertigation systems used in greenhouses are potentially orders of magnitude more sensitive than current legislation would suggest. It may be necessary to monitor whether heavy metals and possibly new process contaminants introduced in the P recovery process can co-accumulate in the P fertiliser and ultimately in the harvestable part of the crop posing new hazards to the consumer.

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Visual material

"Plants in the greenhouse full of light" by Y production/Shutterstock.com
"Top view of group of primary circular sedimentation tanks for sewage cleaning" by Kekyalyaynen/Shutterstock.com
"Ripe tomatoes in the Greenhouse" by Leonidovich/Shutterstock.com