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Combination of technologies for nutrient recovery from wastewater: A review

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ABSTRACT

The growing human population is increasing the need for crop production, which has resulted in elevated requirements of Nitrogen-Phosphorous-Potassium (NPK) fertilisers. This tremendous demand cannot be sustained on traditional processes, which cause significant resource depletion and unacceptable environmental impacts due to their heavy reliance on fossil fuels. To overcome this, alternative sources to obtain fertilisers have been explored, including the recovery of nutrients from wastewater and waste streams. However, this approach faces several challenges, such as the dilution of the streams, low public acceptance, and lack of support. With the aim of surpassing these barriers, the present study provides a review of existing Research & Development (R&D) projects in the field, comparing the available technologies to identify the optimal train of technologies for nutrient recovery: Anaerobic Digestion followed by the valorisation of the digestate (directly or producing P-based fertilisers such as P salts, CaP, H_3PO_4 and P_2O_5) and the liquid fraction (obtaining struvite, ammonium sulphate/nitrate, and reclaimed water). Moreover, an innovative strategy for nutrient recovery based on the decentralised treatment of separated concentrated streams is proposed as a useful strategy for valorising nutrients, developing a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis. Finally, non-technological strategies are suggested to mainstream waste valorisation, aimed at overcoming social barriers by promoting stakeholder acceptance and producing recycled fertilisers with low associated rejection. Nutrient valorisation through the decentralised treatment of source separated waste/wastewater using optimised train of technologies seems a sustainable strategy for addressing the current and future massive demand of fertilisers.

1. Introduction

By 2050 the world's population will reach more than 9 billion. To feed this growing population, crop production must increase by 70% (FAO, 2009). In this context, the projected demand for nitrogen (N) and phosphate (P_2O_5) fertilisers is estimated to reach up to 185 Mt (million tonnes) and 70 Mt, respectively (Bindraban et al., 2015). However, nutrients such as phosphorus (P) are a finite resource. Most of the P applied to agricultural land comes from phosphate rock, with limited and unequally distributed reserves (Cooper et al., 2011) which have given rise to geopolitical concerns (UNEP, 2011). After N and P, potassium (K) is the third major nutrient for plants and crops, being 90–95% of the total K production consumed for fertiliser making (Jena, 2021). Although potash is considered a non-critical material (European Commission, 2020), its production is concentrated in 6 countries, which have a strong influence in setting the potash price in global markets (Ciceri et al., 2015). In parallel, to avoid eutrophication of water bodies, European Union (EU) legislation regulates nutrient emissions to the environment (Council Directive 91/271/EEC, 1991). Nowadays, modern municipal wastewater treatment plants (WWTP) remove 80–90% of the P and >70% of N to fulfil discharge limits at considerable expense: the energy consumption performance of nitrification/denitrification

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systems ranges from 5 to 15 kWh/kg N (Wu et al., 2021). In contrast, nutrients present in the wastewater produced by 30 people (in Europe 4.5 kg N + 0.5–1.5 kg P + 0.5–1.7 kg K per person and year) (Simha and Ganesapillai, 2017; Spångberg et al., 2014) could be used to fertilise about 6–7 tonnes of wheat, producing food for twice as many people (Alberta Government, 2012; Jahan and Amiri, 2018; Malghani et al., 2010).

The P present in WWTPs can be recovered from the liquid phase (i.e., untreated wastewater inflow or the effluent from a treatment unit such as the supernatant from a digester) (Vinardell et al., 2023), sludge or ashes (after sludge incineration). Struvite precipitation in sludge digestate after dewatering allows 35–60% of P recovery (Chrispim et al., 2019), and when enhanced with sludge lysis, 70–80% of P can be recovered from the liquid fraction obtained after the sludge lysis, but even then, the solid fraction still contains the majority of the P. Extraction of P from the ashes after sewage sludge incineration (80–95% of P recovery) is solely applied in a few countries, e.g., Germany, because of its costs and environmental issues (Cornel and Schaum, 2009). Comparing the flux entering a WWTP with the treated liquid fraction, usually <50% of P and <5% of N is recovered with the available technologies, since, especially in the case of N, the processes are intensive and not cost-effective (Shaddel et al., 2019).

Some bottlenecks that limit the nutrient recovery in WWTP are related to economics and market (Kehrein et al., 2020). Current P recovery costs still exceed conventional P ore costs: cost effectiveness of struvite recovery processes strongly depends on profits from struvite sales, while P recovery from sludge incineration ash requires specialised and expensive incinerators. Moreover, nutrient quantities recoverable from wastewater are low compared with industrial production rates, since the highly diluted municipal wastewater limits the efficiency of recovery technologies. Low N concentrations in wastewater make ammonium recovery uneconomical, and struvite precipitation requires a concentration of > 50 mg P per litre (Mehta et al., 2015) to be economically viable. Additionally, the quality of the recovered resource is not always high enough to compete with conventional products. Environmental and health risks are also an important barrier to resource recovery in WWTP. The use of recycled fertilisers may entail risks to human health or the environment, since they may be contaminated with emerging pollutants and heavy metals. Finally, societal and political barriers also jeopardise the potential nutrient recovery from waste and wastewater. User acceptance of resources recovered from wastewater may be low due to fears or misconceptions about the risks they pose. Regarding regulation, resources recovered from wastewaters are currently legally classified as wastes, which hinders their market uptake (EurEau, 2021), and there is a lack of legislation on the in-field application of struvite and other recovered products.

One way to overcome some of the bottlenecks mentioned above is to recover the resources directly from source separated domestic wastewaters such as blackwater (BW) as an alternative to centralised wastewater treatment. Without the addition/mixing/dilution of/with other waste streams, such as greywater, or municipal or industrial wastewater, the available carbon and nutrients are concentrated, thus favouring the recovery of energy and nutrients (Yee et al., 2019). This approach would not entirely replace existing conventional centralised systems, but it can be an attractive alternative where centralised systems do not exist (e.g., rural/isolated areas, new buildings); existing sewerage is old or leaky, and its replacement or upgrade is too costly; or existing WWTPs are overloaded.

The aim of the present study is to evaluate and contrast the available technologies for nutrient recovery, with special focus on decentralised systems. To that extent, a review of current R&D projects about nutrient valorisation from domestic wastewaters has been performed, developing a comparative assessment of the implemented processes to finally propose an optimal train of technologies for nutrient recovery. An investigation on the opportunities and barriers for the implementation of these technologies is included, as well as a SWOT analysis of decentralised treatments as sustainable and cost-efficient strategy for alternative fertiliser production.

2. Rationale for development of optimised combination of technologies for nutrient recovery

The present work was performed in the framework of the Horizon 2020 project Run4Life (Recovery and Utilization of Nutrients 4 Low Impact Fertilizer), which proposes an alternative strategy for improving nutrient recovery rates and material qualities, based on a decentralised treatment of segregated BW, kitchen waste and greywater combining existing wastewater treatment technologies with innovative ultra-low water flushing vacuum toilets for concentrating BW, thermophilic anaerobic digestion (TAD) as one-step process for fertilisers production and bio-electrochemical systems (BES) for nitrogen recovery. For the development of the optimised train of technologies for nutrient recovery, firstly a selection was made of research and development projects relevant to nutrient recycling and management. The inventory was based on a list published and updated every 1–2 years by ESPP (European Sustainable Phosphorus Platform), (Version used January 2020).

The selection of 40 projects (Table S1 in supplemental information) was based on the following criteria: (i) Projects which treated agricultural or urban wastes or wastewaters applying the same technologies applied in Run4Life and (ii) projects treating household or office wastewaters with similar or different technologies to the ones applied in Run4Life. Table S1 gives an overview of technological solutions for different organic streams and products recovered. These results of the projects and technologies were compared and used to eventually design an optimised treatment and recovery system for nutrients used as fertilisers in agriculture. The technological solutions listed in Table S1 have been classified depending on the product obtained: NPK fertiliser, struvite, ammonium nitrate/sulphate, P-fertiliser and finally water treatment and reuse (see following sections, from 3.1 to 3.5).

3. Results and discussion

In the Run4Life project, nutrient recovery was applied at several demonstration sites (https://run4life-project.eu/) across Europe, with different combinations of technologies and resulting products. The 'Nieuwe Dokken', a new residential district in Ghent, Belgium, has implemented wastewater treatment and resource recovery technologies for 430 houses and a variety of other buildings, serving around 1200 people equivalents. Vacuum collected toilet wastewater (BW), organic kitchen waste and greywater are collected and treated for optimal resource recovery. The goal is to reuse all the treated wastewater, by recovering nutrients (struvite) and energy (biogas) and providing the neighbouring industry with process water. At Lemmerweg-oost (Sneek, The Netherlands), the BW of 32 houses is collected with newly developed dual-flush vacuum toilets and treated in an up-flow anaerobic sludge blanket (UASB) reactor. Biogas is produced by TAD, and the effluent and solid fraction of the TAD are hygienically safe for direct use as NPK fertilisers. The third demo-site is located at Porto do Molle (Vigo, Spain). The office building hosts around 40 small and medium enterprises, acting as a business centre and business incubator. The average occupation is around 200 people. It is equipped with segregated grey and blackwater collection in all bathrooms. Greywater is treated and reused for toilet flushing. BW is treated to recover energy, nutrients for fertigation or other fertiliser products. Oceanhamnen (Helsingborg, Sweden accommodates an innovative waste and wastewater management system for around 320 apartments and several office buildings, amounting to around 1800 people equivalents. Vacuum collected toilet wastewater (BW), organic kitchen waste and other domestic wastewater (greywater) are separately collected and treated, aiming for maximum resource recovery.

Fig. 1 shows a diagram with the demo-sites location and a summary of the recovered resources.

Fig. 1. Demo-sites information and location.

In the following sections, a brief description of the Run4Life technologies is given for each of the fertiliser categories. Moreover, the advantages and drawbacks of the technological solutions applied in other projects (presented in Table S1) are described in the corresponding section, allowing a discussion on the possibilities of these technologies or approaches to replace or complement Run4Life's technologies.

3.1. Technologies to obtain NPK (solid & liquid) fertiliser

NPK fertilisers are solid or liquid products that contain N, P and K instead of tailoring the content towards only one or two of these nutrients. In Run4Life different anaerobic digestion technologies were used that produced liquid and solid digestate NPK fertiliser. Moreover, the anaerobic process produces biogas, which can be valorised as an energy source. AD was applied at all four demo-sites. In Sneek, novel dual-flush vacuum toilets (Todt et al., 2021) were used to produce a highly concentrated BW, that was subsequently treated by TAD. By working at high temperatures (multiple days at 55 °C), hygienisation of the liquid (aqueous phase) and solid (sludge) NPK fertilisers can be achieved (Moerland et al., 2020, 2021).

In Vigo demo-site, an Anaerobic Membrane Bioreactor (AnMBR) was used to treat BW from an office building, separately collected using conventional gravity toilets (3.0–4.5 L/flush) and urinals. The solid fraction (sludge) can be used as NPK fertiliser after a hygienisation process. The nutrient-rich liquid effluent, free of pathogens and solids due to processing with the ultrafiltration membranes, can be used for fertigation. The biogas yield was modest due to the low concentration of organic matter in the BW.

In both Ghent and Helsingborg, vacuum toilets and UASB reactors were applied. Two UASB reactors were implemented in the Helsingborg demo-site for separately treating food waste and BW from conventional vacuum toilets, as in Sweden, source-separated toilet wastewater and food waste each have a different certification for agricultural use. Biogas was produced by both anaerobic reactors, the produced digestate of each UASB was dewatered. The combined liquid fraction was further treated for struvite and ammonium sulphate recovery, by struvite precipitation and ammonium stripping. These products were mixed with the dewatered sludge to obtain tailored optimised solid fertilisers (NPK pellets, Fig. 1). The UASB reactor implemented in Ghent treated a mixture of BW from conventional vacuum toilets and kitchen waste slurry. Struvite was recovered from the liquid fraction of the digestate whereas the solid fraction could be treated in an external facility to obtain phosphoric acid using the EuPhoRe process. This last recovery technology has not been applied within the Run4Life project, but the option was explored. Table 1 shows the state-of-the-art technologies for production of NPK fertilisers compiled from the projects listed in Table S1, highlighting their advantages and drawbacks to study if they could replace or complement the Run4Life's technologies.

3.2. Technologies for ammonium nitrate/sulphate recovery

Run4Life project developed an innovative BES technology for N removal at laboratory scale. A BES operating in Microbial Electrolysis Cell (MEC) mode achieved 70–80% N removal (using an initial concentration of 1 g-N/L) and 40–50% N recovery as liquid fertiliser (ammonium nitrate). This system functioned in a similar way as the BES systems mentioned in Table 2. Those systems were running on relatively clean and concentrated water streams like urine. At the Run4Life Vigo demo-site the COD concentration and the N content of the collected BW were too low (due to collection via conventional toilets) to successfully implement the developed BES. So, the carbon and ammonia concentrations of the BW were increased artificially and, the BES system was tested for treatment of this concentrated BW. The performance on real spiked BW was around 20% lower compared to performance with synthetic feeding, in terms of energy, N removal and recovery (Losantos et al., 2021). These results suggest that the BES is highly feasible for highly concentrated BW. Mostly, because BW contains significantly more organic matter than urine, and organic matter may hamper

Table 1
State-of-the-art technologies for NPK recovery (other projects than Run4Life).

Technical solution description	Opportunities	Barriers
Chemical extraction process (from ashes) to obtain NPK solid fertiliser (NEWFERT)	New innovative technology that has been patented by D&M and Fertiberia (EP17382535.7: PROCESS AND INSTALLATION FOR THE RECOVERY OF PHOSPHORUS FROM WASTE INCINERATION ASH, date of embargo: 02/02/2019). The obtained NPK fertiliser in granulated form facilitates its application. The product has been agronomically tested in trials with plants and were applicable to substitute the conventional raw materials, without reduction of the fertiliser efficiency. Low energy consumption.	Reagents are needed for acidification and neutralization. Low density and/or extreme levels of pH in biowaste materials make pre-treatment necessary.
Acidogenic fermentation + AD from agricultural waste to produce biogas and fertilisers (NoAW)	The separation of both processes allows to obtain different products (volatile fatty acids (VFAs), H_2), which are not obtained in UASB. The H_2 and remaining material is used to produce biogas and NPK fertiliser. Biogas production in the pilot-scale biorefinery platform: 15 m^3/day (Righetti et al., 2020).	Separated processes need more space (higher footprint). Complex process control and design.
Dynamic Composting of P-rich biological sludge to obtain biofertilizer (SMART-Plant)	Biofertiliser with high stability and N and P content up to 5% of dry matter. Composting of sludge allows a direct and safe use in agriculture. Advanced aeration control for an optimal organic carbon mineralization by maximizing the biological activity. Reduction of greenhouses gases emissions and energy consumption for aeration compared to conventional composting.	Composting takes several months: Mineralisation and sanitation: 15–20 days and curing and stabilization: 30–60 days.
Nutrient recovery by reverse osmosis (RO) from liquid fraction of AD to produce mineral N, K concentrates (SYSTEMIC)	The N-rich liquid fraction is processed into a nitrogen-potassium (NK) concentrate and clean water through a combination of dissolved air flotation (DAF) and membrane filtration system: microfiltration, RO, and ion-exchange.	Elevated cost of membrane technologies (investment, operation, cleaning, replacement), although it would depend on the value of the obtained product. Moreover, RO requires the addition of H_2SO_4.
Anaerobic thermophilic digestion of manure and food waste (SYSTEMIC, ManureEcoMine)	Thermophilic digestion ensures a better control of pathogenic microorganisms in the digestate. Biogas production per tonne of feedstock: 170 m^3/t (SYSTEMIC).	
Aerotherm reactor hydrolysis and acidification + filtration + carbonator + anaerobic digester to turning biosolids into cleaners and fertilisers (RENEW)	Separation of both processes allows to obtain different products (H_2, VFAs), which are not obtained in the UASB, since those intermediate products are finally digested to biogas. The final digestate would be an NPK fertiliser.	The separated process requires more space, which can be a problem in an urban/domestic environment.
Pyrolysis of solid fraction to obtain biochar as soil improver (BIOECOSIM)	60% conversion to biochar as well as pyrolysis gas for valorisation in a Combined Heat and Power (CHP) plant. Integrated thermal processing unit consisting of a Super-Heated Stream Dryer (SHSD) and a super-heated steam pyrolysis reactor.	The obtained product's value cannot cover the high process costs. This could be (partly) compensated by lower sludge handling costs due the greatly reduced volume.
Two-stage process for bio-granule/organo-mineral fertiliser production from dewatered digested sludge (End-o-sludg)	Fertiliser with a guaranteed nutrient content (NPK of 10:4:4) giving similar yields to the conventional fertilisers when applied to cereals and grassland crops.	The estimated unit cost to produce the obtained organo-mineral fertiliser was €162/t. The greatest part of the unit cost was due to the supplementary nutrient input (N and P) (53%).
Two-stage anaerobic digestion of digested and raw sludge with thermal pre-treatment (ROUTES)	The separation of both processes allows diversifying the obtained products. The thermal pre-treatment improved anaerobic digestion in terms of volatile solids reduction and biogas production and produced sludge of good quality suitable for the use in agriculture without restrictions.	Digestate dewaterability is worsened. The thermal pre-treatment consumes energy. The separated process requires more space, which can be a problem in an urban/domestic environment.
Anaerobic side stream reactor for sludge stabilisation (ROUTES)	The process improved nitrification and sludge filterability.	If digestate is accepted as NPK fertiliser this extra step would not be needed.
Composting of solid fraction (NIREC, SANBOX, MIX-FERTILISER, DIGESMART, Biorefine)	It is a well-known technology for sludge stabilisation.	
Bio-electrochemical systems with biochar* (Biofuelcell APP project)	Organic and inorganic carbon, N, and other macro- and micronutrients recovery.	The process is carried out for treating swine farming wastewater. It is unsure how it would perform with other substrates.

* Low TRL. The technology is still being developed and away from larger scale application.

performance of the system. The BES needs to be optimised further before it can be successfully implemented in a system with source separation. At the Helsingborg demo-site, the liquid effluent coming from struvite precipitation is collected in a stirred tank for temperature increase to 65 °C and pH adjustment to pH 10 using NaOH. Subsequent stripping of ammonia as gas and extraction of ammonia sulphate using sulphuric acid was implemented. Covid-19 crisis affected the operation and start-up of this technology, so unfortunately, the steady state operation has not been yet achieved. However, it is an old and reliable technology,

Table 2

State-of-the-art technologies for ammonium nitrate/sulphate recovery (other projects than Run4Life).

Technical solution description	Opportunities	Barriers
BES for N recovery* (Newfert, ValueFromUrine)	The use of urine instead of BW allowed to obtain 95% recovery of N.	In the case of Newfert, the N is not recovered as fertiliser.
Ion exchange (SMART-Plant)	High recovery rates: Up to 97% of ammonia.	N is recovered as ammonia-rich solution instead of as fertiliser.
Ammonia stripping of the liquid fraction to obtain ammonium sulphate (SYSTEMIC, ManureEcoMine, NUTREC, MIX-FERTILIZER, Biorefine, DIGESMART, Nutricycle, Nutrient Clearing House).	Nitric acid can be used in the scrubbing step due to higher value of ammonium nitrate in comparison to other ammonium fertilisers, achieving high N content (18% N) in the ammonium nitrate solution (MIX-FERTILIZER). The side-stream stripping process allowed to increase 2.5-fold the organic loading rate without affecting the digester performance (ManureEcomine).	Raising the pH above 10.5 considerably increases the operative cost but does not represent significant improvement in the recovery rate (MIX-FERTILIZER).
Ammonia stripping with enzyme pre-treatment (NIREC)	Allows ammonia release, increasing its concentration in the stream and thus favouring the stripping process.	The cost of the chemicals can be higher than the cost of the ammonium salt recovered.
Ammonia stripping with pre-stripping unit with CO_2-stripper (ROUTES)	Allows reducing NaOH consumption by nearly 50%	The cost of the chemicals, as the cost of the acids can be higher than the cost of the ammonium salt recovered.
Membrane contactors (BIOECOSIM, ENRICH)	Allows obtaining ammonium sulphate as an alternative technology to ammonia stripping, using tubular or flat plate gas permeable membranes, eliminating the necessity of a stripping process.	The process requires high N concentrations in the stream (more than 2 g-N/L)
Adsorption into zeolites (ENRICH, NECOVERY)	In the ENRICH project, the technology is applied to the sludge liquor obtained from AD sludge dewatering, achieving over 96% N-NH_4^+ removal. The saturated zeolite could be used as a substrate for slow N release in soils.	If solids are present in the stream, it must be preceded by an ultrafiltration step which may make the process too expensive.

[*] Low TRL. The technology is still being developed and away from larger scale application.

so it is expected to remove 75% of the N content in the treated liquid stream. The technology is comparable to the stripping technologies mentioned in Table 2, but without the pre-treatment by enzymes of stripping of CO_2. These pre-treatments could lead to lower chemical consumption in at the demo-site. In Sneek, N was not recovered as a separate component and in Ghent, N was not recovered.

The other technologies mentioned in Table 2, may be more or less suitable for the Run4Life concept. Zeolites loaded with ammonium could be applied as slow-release fertiliser, in fact, (Costamagna et al., 2020) demonstrated its efficiency for strawberry plants. The application of membrane technologies for systems operated on BW is not likely a good alternative since the N concentrations are too low to be feasible for successful extraction.

Systems targeting N recovery via stripping often aim to produce ammonium sulphate. Also, within the framework of Run4Life ammonium was sorbed in a sulphate solution. The application of ammonium sulphate as a fertiliser may lead to leaching of sulphur to soils. Ammonium nitrate production and subsequent usage as fertiliser may be more appropriate, also because this form solely contains N and therefore is more easily blended for optimal N:P:K ratios. Naturally, in its solid form ammonium nitrate has it disadvantages but as a liquid it is sold (under conditions) for fertilisation. When applying stripping processes for N recovery it would also be possible to produce other formula, e.g., ammonium carbonate and others. Whether this is applicable within the overall Run4Life concept and/or desirable from a fertiliser perspective remains to be assessed.

3.3. *Technologies for obtaining struvite fertiliser*

The recovery of phosphate from wastes and wastewaters has been addressed in a wide variety of conditions. The projects and commercially available technologies aim to recover phosphate mainly as struvite, calcium-P salts and to a lesser extent K-struvite. Technologies are used to process digestate of manure (or fractions thereof), which in some cases are pre-treated (e.g., by acidification) to mobilise the P, reject water or sludge digestion on the one hand and ashes of incinerated sludges on the other hand. Since the Run4Life streams from the different demo-sites to be treated for P-recovery were different, not all technologies or approaches used in other projects are appropriate or applicable. Since the P concentration in the BW obtained in Run4Life's Vigo demo-site was too low to technically introduce a precipitation system, struvite precipitation was demonstrated in a nearby WWTP operated by Aqualia. This reactor (Garrido Fernández and Crutchik Pedemonte, 2017), based on an up flow fluidized crystallization with increasing diameters to form large crystals, used industrial grade magnesium oxide (MgO) as a cheap magnesium and alkali source. The reactor was operated at pH 8.0–8.3, obtaining an average P-content in struvite of 11–12% of dry weight, which makes it comparable to the commercially available technologies described in Table 3. For the other demo-sites, BW was collected with vacuum toilets, which led to a more concentrated stream. BW (and organic kitchen waste) was separately collected and treated in UASB reactors. In Helsingborg, struvite was recovered from the liquid effluent after digestion of BW and food waste after treatment in an aerated tank to remove CO_2 (via degassing) and increasing the pH (by addition of NaOH if needed). The struvite precipitation took place in three batch reactors in order to continuously run the struvite precipitation process: one reactor was being filled, one was allowing precipitation and one was being always drawn. Magnesium chloride ($MgCl_2$) was added as precipitant and struvite was separated using a hydro cyclone. The recovered struvite was mixed in specific ratios with potassium chloride and hygienised sludge from the two anaerobic digesters to produce pelletised NPK fertilisers (with an increased market value due to tailor made NPK-ratios).

In Ghent, BW and organic kitchen waste were collected separately, however both flows enter the same vacuum collection tank where they became mixed and treated together in an UASB reactor. The effluent of the UASB reactor flowed to the struvite reactor where $MgCl_2$ was added as precipitant and no additional pH adjustments were made. In Sneek, the thermophilic UASB running on vacuum collected highly concentrated BW produced a P rich sludge, and a NPK containing effluent, which were not processed further and could be used as P containing streams as such. Table 3 shows the state-of-the-art processes for struvite precipitation. The technologies applied in Run4Life are comparable to those used in the projects described in Table 3. This is to be expected given the similarity in composition of BW (in combination with food waste) and organic streams rich in nutrients like manure and sludge. The electrochemical recovery method mentioned in Table 3 is completely different from the technologies applied in Run4Life. Since this method is mostly applied in sludge dewatering liquids which contains less organic material than the UASB effluents, it is difficult to assess what the

Table 3
State-of-the-art technologies for struvite fertilisers (other projects than Run4Life).

Technical solution description (project where used specified in brackets)	Opportunities	Barriers
Struvite precipitation (SMART-Plant, BIOECOSIM, ManureEcoMine, NUTREC STRUVITE, ValueFromUrine, ENRICH, PhorWater, Biorefine, NEREUS, Nutricycle, Phorwärts, POWER, Sustainable Airport Cities, NEWFERT). The same technology as used in Run4Life, with differences in the reactor configuration, and chemicals used.	SMART-Plant's SCEPPHAR (short-cut enhanced P and PHA recovery) process allows up to 85% N removal, struvite recovery (45–63% of the influent P) and sludge rich in PHA (6.9–9.2%), decreasing energy costs by up to 20%. The use of nutrient-rich sources, such as manure and urine, allowed up to 65–98% (ManureEcoMine) and 95% (ValueFromUrine) nutrient recovery.	Struvite precipitation usually requires the addition of magnesium and other chemicals for pH control. The use of manure requires a pre-treatment step (acid leaching) to dissolve the P into the liquid fraction. This can be done via chemical addition or via microbial processes (NEWFERT project).
Crystalactor, Pearl and Airprex (P-REX, Phos4You).	Commercially available technologies, with a dedicated reactor (up-flow-fluidized bed with large crystallisation surface, up-flow fluidized bed reactor with zones of increasing diameter and continuous stirred reactor with struvite recirculation) for precipitation of phosphate either as struvite or Ca-P. Technologies deal with water phase or sludge line.	Influence of presence of organic material on product quality. Struvite precipitation requires the addition of magnesium and increase the pH, which increases the costs.
Electrochemical precipitation of struvite (ePHOS).	98% of soluble P recovered from sewage sludge dewatering liquors, food, or industrial wastewater (as struvite or K-struvite). No need for chemical addition, magnesium is provided by sacrificing electrode.	The electrochemical process is operated with H_2O conversion at the cathode and requires input of energy.

*Low TRL. This technology is still being developed and away from larger scale application.

recovery rate of the precipitated P would be in the BW.

3.4. *Technologies for obtaining other P-fertiliser*

During the Run4Life project, recovery of dedicated P fertilisers at the demo-sites has been explored but not yet implemented. At the Ghent demo-site it was planned to test recovery of phosphoric acid from sludge ashes through the EuPhoRe process (see below). However, by the end of the project in November 2021 there had not yet been a need to extract sludge from the UASB reactor. It is the intention of the demo-site managers to test P-recovery from the sludge as soon as this becomes available in the operational process. Moreover, calcium phosphate (CaP) production by granulation simultaneously with anaerobic digestion is being tested at laboratory scale in Sneek. This has been previously achieved at lab scale for mesophilic anaerobic digestion of BW, but not for thermophilic (55 °C) or higher temperatures. The BW produced at the Sneek demo-site has at least 2 times higher concentration of solids and organics than the BW previously used for CaP granulation. The reactor and process design used in the laboratory tests are adaptations of those used by (Cunha et al., 2019), and still under development. Table 4 shows alternative technologies for P recovery, gathered from the diverse

Table 4
State-of-the-art technologies for obtaining P-fertiliser (other projects than Run4Life).

Technical solution description (project where used specified in brackets)	Opportunities	Barriers
Calcium phosphate from the liquid fraction (BIOECOSIM, P-REX, NEREUS)		BIOECOSIM and NEREUS projects use the effluent after anaerobic digestion for P recovery and P-REX recovers P from ash or sludge.
P-stripping from the solid fraction to obtain calcium phosphate (SYSTEMIC)	It could be a good alternative in countries where the digestate cannot be used directly for agriculture.	
Ion exchange (SMART-Plan)	Up to 95% of P as calcium phosphate, obtaining a high purity product with 13% P content and low impurities (Al < 0.4 mg/g, heavy metals < 0.1 mg/g).	
BIOPOL process (End-o-sludg)	The resulting complex has a high P content (24.3% P_2O_5) which compares favourably with struvite (26.9% P_2O_5) without needing Mg addition. A recovery rate of over 90% was readily achievable for liquor streams with concentration over 100 mg P/L.	BW in Run4Life has typical >250 mg P/L. We would have to add 5 g of BIOPOL per L of BW with the capacity mentioned. Effectivity of Ca addition is not clear yet. IPF is already done in TAD unintentionally as part of the process.
DM-Phos process (NEWFERT)	This process obtains calcium phosphate from insoluble ashes, by adding $Ca(OH)_2$ and H_2SO_4 (biowaste).	
FiltraPHOS process: Adsorption of P from a liquid stream using adsorbent $CaCO_3$ as adsorbent (Phos4You)	After filtration, the sorbent material containing the recovered P can be directly applied to land as fertiliser of as an intermediate for industry. It could be an additional technology after struvite or CaP precipitation to recover the remaining P in the liquid stream.	
Membrane crystallisation (RecoverP)	The process can be used for concentration and precipitation of phosphate from low concentration feeds. It could be an additional technology after struvite or CaP precipitation to recover the remaining P in the liquid stream.	
Phosphorus hydrolysation with enzymes from agricultural residues (PhosFarm)	The process allows to increase P recovery up to 80% as phosphate salts with comparable efficiency to commercial P-fertilisers. Therefore, it could be an alternative technology to be evaluated for P recovery from the solid fraction coming from the anaerobic digestion in	

(*continued on next page*)

Table 4 (*continued*)

Technical solution description (project where used specified in brackets)	Opportunities	Barriers
	case it could not be applied directly (due to legislative restrictions).	
EuPhoRe process: Thermochemical solution (Phos4You)	Two-step process (anoxic 650–750ºC, aerobic 900–1000ºC), obtaining phosphate ash 12–20% P_2O_5 from dewatered sludge. It could be an option for countries where the solid fraction of the anaerobic sludge cannot be directly used for agriculture.	Previous dewatering of the sludge is needed, and the thermal process requires high temperatures.
Tetraphos process (Phos4You, Phorwärts) / Acid leaching of P from the sludge (solid fraction) + precipitation as Ca(Mg) phosphate (Phos4You) / Hydro-thermal carbonisation + acid leaching (AVA-CleanPhos) / Incineration of sludge obtaining P-ashes (Nutrient Clearing House)	Acid extraction of P from sewage sludge incineration ashes. Phosphoric acid, calcium phosphate or struvite can be obtained from sludge. It could be an option for countries where the solid fraction of the anaerobic sludge cannot be directly used for agriculture	Note that the previous dewatering + incineration (drying) of the sludge is needed, which may make the process expensive. The process would not be economically feasible to obtain struvite or calcium phosphate
Calcium-silicate-hydrate as P adsorbent obtaining calcium phosphate from the digested sludge (FIX-PHOS)		Recovery rates of 25–40% are not competitive with those obtained in the struvite precipitation process (at least 85%).

projects listed in Table S1.

3.5. *Technologies for water/effluent treatment and reuse*

In Run4Life's Vigo demo-site, the effluent from the AnMBR was disinfected through UVC-LED and ozone for being treated as fertigation water. The ozone process treated a flow from 0.3 to 120 L/h. The ozonation column with corona discharge injection of ozone, had a volume of 10 L and was able to remove pharmaceuticals and other contaminants of emerging concern such as ibuprofen (30%), carbamazepine (86%), diazepam (6%), fluoxetine (73%), tonalide (83%), roxithromycin (63%), bisphenol A (65%), estrone (30%) and galaxolide, trimethoprim and triclosan (under limit of detection/quantification). These removal efficiencies were obtained for the maximum dose of ozone (15.9 mg O_3/L) (Run4Life report D3.2, 2020). However, the efficiency of ozonation is compound-dependent and some criteria should be established to select the optimal ozone dose (for example, considering the concentration or the potential toxicity of each organic micropollutant) (Paredes et al., 2018). The UVC-LED (Aquisense Technologies) system had a treatment capacity of 14 L/min with an expected energy demand of 0.45 kWh/m^3 when treating a flow of 0.86 m^3/day. However, the energy demand could be reduced notably as the capacity of treatment of the UV-LED equipment was higher than the treated flow. On the other hand, the reduction in the transmittance properties of the liquid permeate from AnMBR treatment decreased the effectiveness of UV-LED disinfection, and applicability of this technology to treated wastewater is still under research. Optimal values according to the producer was as low as 0.03 kWh/m^3 and 0.05 kWh/m^3 were estimated for the treatment of the greywater in the demo-site (Run4Life report D3.2, 2020). Table 5 shows the technological solutions for obtaining reclaimed water for irrigation developed in the evaluated projects, all of them based on the use of solar radiation as renewable source of energy reducing the costs associated to the electricity consumption.

Table 5
State-of-the-art technologies for water/effluent treatment and reuse (other projects than Run4Life).

Technical solution description (project where used specified in brackets)	Opportunities	Barriers
Lumbrifilter + Daphnia filter + Bio-Solar Purification (BSP) + UV treatment (INNOQUA)	Lumbrifilter and Daphnia filter seem to be innovative alternatives for the removal of organic matter. Moreover, BSP could be a good alternative to the UV treatment in countries with significant solar irradiation, reducing the energy demand and associated costs.	The implementation of the BSP system could be restricted to geographical areas with high solar irradiation, reducing its global market share.
Solar driven ultrafiltration for disinfection (INCOVER)	This technology is solar driven, therefore a good alternative to non-renewable energy driven disinfection systems such as UVC in countries with significant solar radiation.	The implementation of this technology could be restricted to geographical areas with high solar irradiation, reducing its global market share. Its economically feasible could be lowered if the technology cannot be coupled to a renewable energy source. Membrane maintenance and replacement can also represent a drawback for its application.
Solar driven electro-chlorination for disinfection (INCOVER)	This technology is solar driven, therefore a good alternative to non-renewable energy driven disinfection systems such as UVC in countries with significant solar radiation.	The implementation of this technology could be restricted to geographical areas with high solar irradiation, reducing its global market share. Its economically feasible could be lowered if the technology cannot be couple to a renewable energy source. Electrode's maintenance and replacement can also represent a drawback for its application.

3.6. *Optimised train of technologies for recovering nutrients from wastewaters*

From the previous comparison of technologies, a train of technologies integrating the most suitable processes for nutrient recovery has been performed. The following figures represent a schematic train of technologies to maximise nutrient valorisation as fertilisers from separated sources (kitchen waste and BW), under two different regulatory frames. In both cases, BW is mixed with kitchen waste (as another source of concentrated organic matter) before being treated through anaerobic digestion. However, both waste streams could be treated separately. The obtained solid fraction could be directly valorised as solid NPK fertiliser (Fig. 2, using TAD to obtain an hygienised product, or TAD/AD followed by an hygienisation process). If not allowed (Fig. 3, AD could be used since no hygienisation is needed), it should be dewatered, from which solid fraction could be valorised by diverse alternative technologies to obtain different P-based fertilisers. The liquid fraction could be valorised using the same train of technologies considered for the liquid fraction coming from the anaerobic digester, obtaining P-based fertilisers, N-

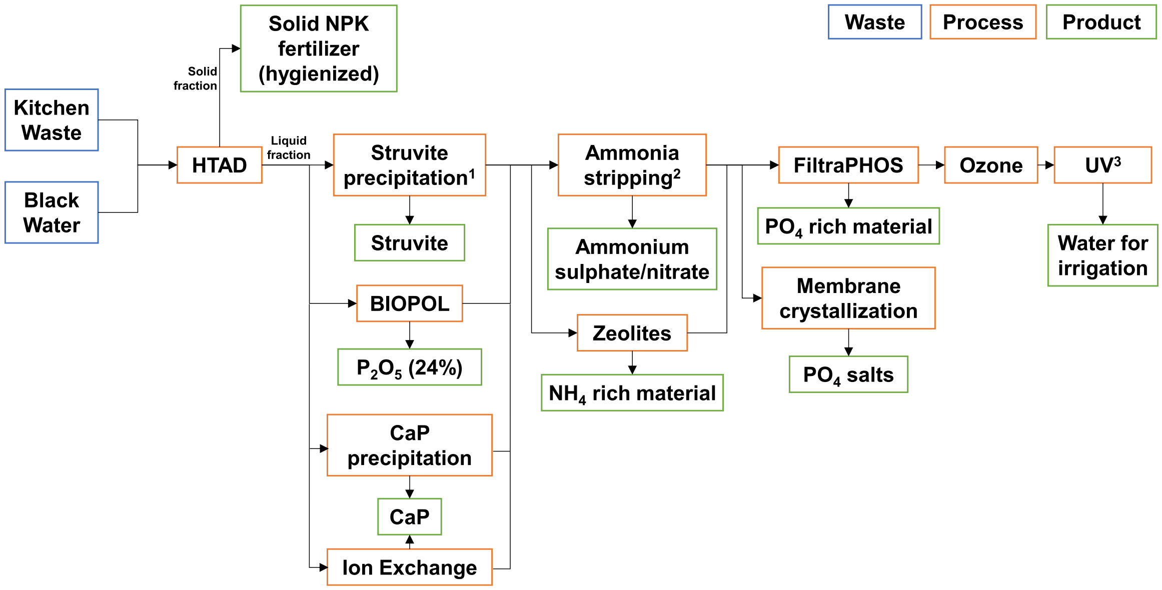

Fig. 2. Optimised train of technologies for nutrients recovery from BW and kitchen waste. [1] Struvite precipitation technologies: conventional, Newfert, Crystalactor, Pearl, Struvia, ePhos. [2] Optimization technologies such as enzymatic pre-treatment and CO_2 stripping could be applied. [3] Solar UV should be used if climatic conditions are optimal. If not, UV-LED allows reducing electricity consumption compared to conventional UVC lamp, although its efficiency when applied to treated wastewater is still under research.

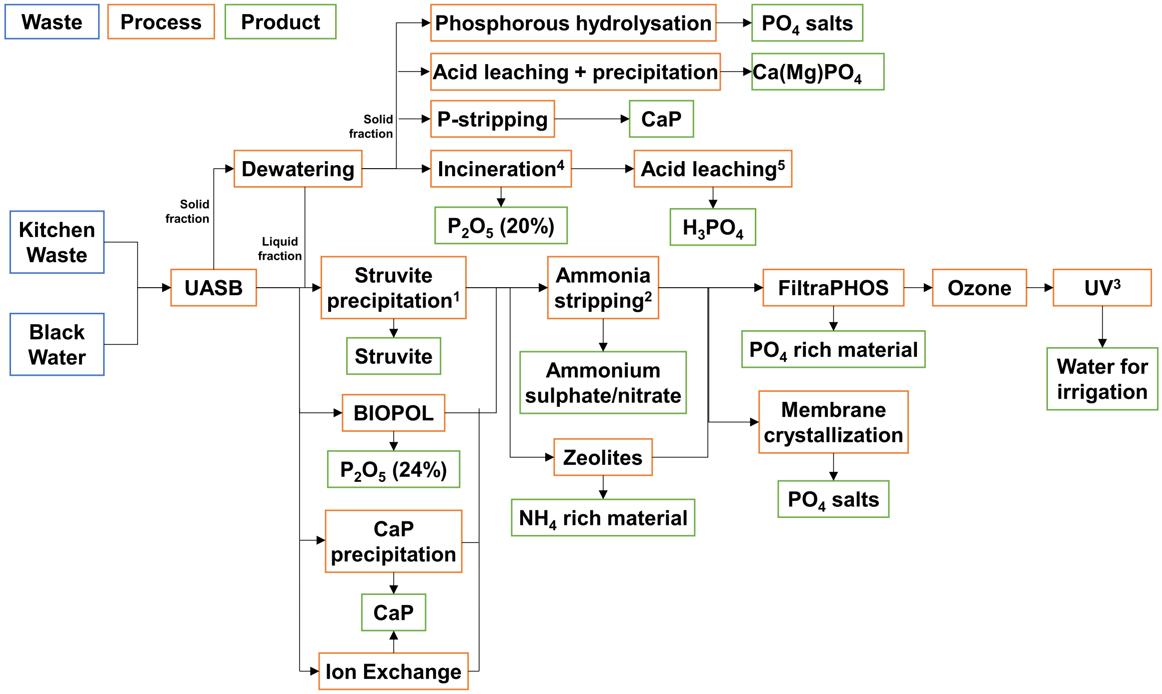

Fig. 3. Optimised train of technologies for nutrients recovery from BW and kitchen waste in countries where sludge cannot be directly used in agriculture. [1] Struvite precipitation technologies: conventional, Newfert, Crystalactor, Pearl, Struvia, ePhos. [2] Optimization technologies such as enzymatic pre-treatment and CO_2 stripping could be applied. [3] Solar UV should be used if climatic conditions are optimal. If not, UV-LED allows reducing electricity consumption compared to conventional UVC lamp. [4] Conventional incineration, hydrothermal carbonisation, EuPhoRe process. [5] Or Tetraphos process.

based fertilisers and reclaimed water for irrigation. The idea is to first recover P and N, and then use "polishing" technologies if P is still present in the liquid stream, with the aim of maximising nutrient recovery after removing recalcitrant pollutants (ozonation) and disinfecting the effluent to obtain reclaimed water for irrigation. If organic matter content after nutrient recovery is still high, a biological treatment could be integrated before ozonation. Several technologies have been arranged in parallel since they could be alternatively used to obtain different products. Although some information about recovery efficiencies has been obtained from current and past projects, these technologies should be evaluated under the same conditions to be able to select the most cost-efficient one (considering capital, operation and maintenance costs and the value of the obtained product).

3.7. Technical options towards decentralised nutrient recovery

This section reviews and proposes the opportunities and barriers and potential strategies to boost the first and to overcome the latter for the decentralised nutrient recovery. Moreover, an analysis of the Strengths, Weaknesses, Opportunities and Threats (SWOT) are summarised in Fig. 4.

3.7.1. Opportunities

Within the conventional linear approach, the solid waste and human excreta are usually directed towards end-of pipe solutions such as landfills or WWTPs where they are contained or partially treated and recovered, thereby still causing unwanted emissions to be released into the natural environment. Beyond current centralised schemes, decentralised nutrient recovery alternatives allow a higher control and potential economies of scale and reduce the need for scarce municipal land and operational costs. Moreover, in situ recovery alternatives allow closing cycles locally, reducing transport distances for residues, fertilisers and food, offering many advantages for citizens, and avoiding fossil-based non-renewable artificial fertilisers (de Kraker et al., 2019).

Source separation and decentralisation allow to minimise treated volumes and transport distances of wastewater (in sewers for discharge and pipes for reuse) and sludge (in trucks), reducing infrastructure needs and energy costs, although vacuum sewers are required. Nutrient recovery can be especially applicable in rural areas, since the recovered N and P can be used in agriculture or to grow photosynthetic microorganisms (e.g., algae) for (proteinaceous) food production. Moreover, farms are perfect places to implement a decentralised nutrient recovery strategy, since they produce large quantities of waste(water) streams (e.g., livestock -pig/chicken/cattle- manure) with high concentrations of nutrients and metals (which could end up in the environment, causing severe pollution problems such as water eutrophication, soil and groundwater pollution) that can be valorised (Guan et al., 2021). E.g., the P content in manure ranges from 4 to 33 g P/kg slurry (highest concentration can be found in pig slurry, lowest in cattle slurry), with a N:P ratio ranging from 2:1–7:1 (Li et al., 2020). Agricultural digestate, especially if derived from livestock manure, is a potential candidate for the recovery of bio-based fertilisers: 180 M tonnes of digestate, which contain high concentrations of N (2–5 kg/m^3) and P (0.5–1.5 kg/m^3), are produced annually in the EU (Rizzioli et al., 2023). The obtained fertiliser products could be applied in the nearby crop fields, which would avoid transport costs, allowing a kilometre zero decentralised nutrient recovery approach.

The decentralised model can be also extended to urban areas as the concept of growing food in the city takes hold within the revolutionary concept of "edible cities" as an applicable nature based solution in the urban environment (Larsen et al., 2013). Moreover, restaurants, hotels, markets, and malls, especially those established in isolated areas (disconnected from the sewage system), are perfect niches for applying Run4Life's decentralised nutrient recovery strategy. Separated BW, kitchen and food/organic waste generated in these locations can be valorised pursuing a zero-waste circular approach. In many countries, part of the organic waste is separated at home, collected and then composted in centralised facilities. The separate collection rates vary from 80% or more in Austria and Slovenia to less than 10% in Bosnia-Herzegovina, Cyprus, North Macedonia, Portugal, Spain and Turkey. On average in 2017, 43% of total municipal bio-waste in the EU-28 was collected separately (European Environment Agency, 2020). As a result of the composting process, a solid and a liquid fraction are obtained, with high content of (stabilised) organic matter and nutrients. The liquid fraction can contain up to 100 mg/L P-PO$_4^{-3}$ and 2500 mg/L N-NH$_4^+$ (Sanadi et al., 2019). Both N and P are in this stream susceptible of being valorised following the technologies specified in Fig. 2 and Fig. 3, according to the local legislation.

Considering the industrial sector, food processing industries usually generate wastewaters with high content of biodegradable organic matter and nutrients. Specifically, total P content ranges between 3 and 100 mg P/L and total N appears in concentrations among 10 and 700 mg N/L, being winery, cheese dairy, olive mill and cassava starch the agro-food industries which generate wastewaters with higher N and P content (Rajagopal et al., 2013). Moreover, decentralised nutrient and water recovery can be an innovative business model for these industries, since they could obtain benefits from the recovered fertilisers and use their own reclaimed water, thus reducing freshwater consumption and associated costs.

Aquaculture systems can also be a niche for the adoption of Run4Life's nutrient recovery technologies and strategy. In aquaculture, solid wastes are primarily derived from the uneaten feed and the faeces produced by the cultured fish, and also other organic remains. In an efficiently managed farm – with controlled dietary strategies to improve feed use efficiency – approximately 30% of the feed will become solid wastes. On the other hand, there are also dissolved wastes, which are products of food metabolism in fish or decomposed food, uneaten feed, being the two major components of concern N and P, since fishes are only able to retain between 25% and 30% of N to 10–49% and 17–40% of P. (Piedrahita, 2003) reported that fish faeces contained 3.6–35% N and 15–70% P, while the amount of N and P as excretory products were 37–72% and 1–62%, respectively of the N and P fed to the fish. The N is mainly excreted in dissolved form as ammonia (NH$_3$), while P is excreted as particulate matter. Nitrate (NO$_3^-$) is the end-product of NH$_3$ oxidation and is generally regarded as safe because it is not toxic to most fish species, even at a concentration as high as 200 mg NO$_3$/L (or ~ 45 mg N/L). However, nitrate can accumulate to levels as high as 300–400 mg/L, depending on the frequency of water exchange. Mixed

Fig. 4. SWOT analysis of decentralised nutrient recovery.

solid waste and wastewater from aquaculture could be, therefore, a good nutrient source to be valorised within a decentralised approach.

Although Run4Life has been conceived as a decentralised strategy, the proposed technologies could be also applied in the centralised WWTP that are currently in use, which produce almost 10.13 million tons (dry solids) of sewage sludge per year in EU (Gendebien et al., 2010), with a nutrient content of 1.0–2.5% P (Mtshali et al., 2014), 10–15% N (Tyagi and Lo, 2013), of which 39% is directly recycled to agriculture. Sewage sludge management represents one of the main costs of WWTP, so in many locations WWTP are already valorising such waste by AD, generating biogas and using the stabilised sludge as NPK fertiliser. Additionally, the liquid fraction obtained by sludge dewatering could be also valorised to obtain N- and P- based fertilisers. If wastewater from centralised WWTP is considered for nutrient recovery, the proposed train of technologies could also be applied, after a pre-treatment for concentrating nutrient content (e.g., ultrafiltration) so they could be efficiently operated.

3.7.2. *Potential strategies to boost opportunities*

Political interest in phosphate sustainability has grown a lot at the European level, as demonstrated by the incorporation of phosphate rock on the European critical raw materials lists in 2014 (European Commission, 2020). The presence of various inter-organizational platforms focusing on nutrient recycling, such as the ESPP, contribute to sustainable developments and implementations, such as struvite recovery. In practice, these platforms serve as a hub for information exchange, and they facilitate communication between all cross-sectoral stakeholders. Therefore, these platforms have helped in accelerating developments at the political and legislative level (de Boer et al., 2018).

Since P availability and needs differ between regions, an effective global governance of this element is required, including clear stakeholders' roles and responsibilities. National policymakers can facilitate the assessment of a region's P vulnerability to scarcity and pollution, and the prioritization, development, and implementation of cost-effective, socially robust, and environmentally sound, context-specific responses for the recovery and efficient use of P. All key stakeholders, the fertiliser industry, water service providers, farmers and so on must actively be involved in the solutions (Kabbe, 2019).

From an economic perspective, the costs for P recovery and the return-on-investment period are highly dependent on the type of technology utilized and size of the plant. Several studies report a return of investment of six years for facilities with capacities of 265 and 3711 m^3/day, respectively. The main driver to recover struvite out of wastewater is the reduction of maintenance costs for the water boards, as in that way the clogging of pipes is avoided. Moreover, given the popularity of circularity and circular economy, recovered nutrients such as struvite can be considered as a green marketing tool for the water board (Mtshali et al., 2014).

From a social point of view, there are several positive externalities linked to the decentralised valorisation of residual flows. Firstly, people become more aware of their own residues production, since environmental consciousness is nowadays a key public policy aim in its own. Secondly, the investment and risk of the waste management task is spreading among the population which alleviates the municipal budget burden of the initiative. Thirdly, the monitoring and control of the organic solid waste treatment could be improved as the treatment and disposal is done by the interested party, who directly perceives both the costs and benefits of their effort (Mayer et al., 2016).

3.7.3. *Barriers*

3.7.3.1. Technology. One of the main barriers of nutrient recovery is the cost of implementing and operating the technologies. Technologies and infrastructure for conventional centralised wastewater treatment are already implemented and have well-known operational costs. Alternative technologies for collection, treatment and recovery are perceived to carry more uncertainties, and many of them are currently more expensive. A change of paradigm towards nutrient recovery from wastewater will be essential in a near future, due to the growing demand and finite natural resources. Therefore, innovation should be focused on optimising technologies for nutrient recovery aiming at reducing operational costs and enhancing their efficiency even at low concentrations.

One of the main costs of these kind of technologies comes from the use of reagents. For example, for struvite precipitation, NaOH (for increasing pH) and a Mg source must be added. In such case, alternative reagent sources should be searched. Recycling of MgO wastes from industry for struvite precipitation is considered, within an integral Circular Economy philosophy. Increasing the circularity of the system under an Industrial Symbiosis strategy can reduce treatment costs, making processes affordable. Another important cost is represented by energy consumption. To reduce energy consumption, it is essential to operate the system under optimised conditions. For example: a certain technology can be cost-effective up to a limit concentration; therefore, is essential to monitor nutrient concentration in order to operate the technology under optimal conditions. In this sense, monitoring and control systems and decision support systems play a crucial role in the optimisation of nutrient recovery processes. Moreover, biogas produced in the AD can be converted by a CHP engine into electrical and thermal energy, to be used in the process (e.g., SYSTEMIC project). Another strategy could be separating the AD process in two reactors: the first one (hydrolysis + acidogenic fermentation) will produce H_2 and VFA (value-added products than can also be valorised to make the process more cost-effective) and the second reactor will produce biogas and NPK fertiliser. In such case, nutrient recovery technologies could be integrated between both steps, since the effluent from the acidogenic fermentation is acid, so nutrients are in solubilised form.

Another barrier faced by nutrient recovery is the concentration of available nutrients, which sometimes is too low to achieve a cost-effective process. To overcome this barrier, the decentralised treatment of separated waste sources is being established as an advantageous deal. Moreover, the use of ultra-low water consumption vacuum toilets allows obtaining a more concentrated BW, from which it is easier to recover nutrients. Alternative strategies could be: mixing the wastewater with solid organic waste to enrich it in organic matter and nutrients or pre-concentrate the wastewater by using membrane technologies (e.g., ultrafiltration), as commented before. In the latter case, the process should be optimised to not increase treatment costs. Intimately related is the size that will be needed for most of the technologies to have optimum values for energy consumption and availability of devices. A small anaerobic reactor may produce a good quality biogas, albeit in a small amount, which will make it more difficult to find a user for the energy. The same holds for fertiliser production: if the production is small, it will be difficult to find a market.

3.7.3.2. Public opinion and market. The public opinion can be also another barrier, since recovered nutrients are products derived from wastewater and people immediately relate this to health issues. Educating society will be necessary to gain product acceptance. The users of fertilisers, farmers, are not aware of the effects of the surplus of phosphate. Growing awareness about the phosphate problem could play a helping hand in the use of recycled phosphates (Mannina et al., 2021).

Finally, the fertiliser market can be characterized as conservative, rigid, and hard to change, so a driver for the use of P recovery products for fertiliser companies and the implementation for water boards is the sustainable label. The green marketing aspect of struvite and other recycled fertilisers is attractive, and it has a positive effect on the society. Another driver in this sense would be the implementation of P recovery products in the fertiliser regulation because certification of struvite might alleviate fears around product safety (de Boer et al., 2018). Moreover, some authors state that upholding the wishes of the market is often overlooked by researchers. The user is not always sufficiently involved in the research process, this indicates that there is a knowledge gap concerning the market applications of struvite and recycled fertilisers (Schipper, 2014).

3.7.3.3. Legal barriers. The former fertiliser legislation in the EU, (Regulation EC No, 2003/2033, 2003) in force until 16 July 2022, only harmonised the quality certification process of mineral/inorganic fertilisers (i.e., EC fertilisers). However, nowadays, there is an increase in the production of fertilisers from organic waste streams or the combination of organic and inorganic materials, which are not covered by this EU Regulation. Instead, the non-EC fertilisers and other fertilising products were until now regulated following national rules, which was a problem because some countries have well-developed regulatory processes for these product types while other have no legislative framework. Therefore, these products had a competitive disadvantage to access to the market, which was an obstacle to both innovation and investment in the circular economy (Klaus, 2020).

From July 2022 onwards, the quality certification process of fertilising products is harmonised across the EU through the *Fertilising Products Regulation* (Regulation EC No. 2019/1009, 2019). In addition to inorganic fertilisers, the FPR harmonises the quality assessment procedures for other fertilising products, such as organic fertilisers, organo-mineral fertilisers, soil improvers, liming materials, plant biostimulants, inhibitors and fertilising product blends (Oni and Reddy, 2021). The new rules allow to: i) open the market for new and innovative organic bio-based fertilisers, ii) provide strict rules on safety, quality and labelling requirements for all fertilisers to be traded freely across the EU (producers will need to demonstrate that their products meet those requirements before affixing the CE mark, iii) divide the EU fertilising products into different product function categories which should each be subjected to specific safety and quality requirements adapted to their different intended uses, iv) specify components that can be used as ingredients in these products, and related safety and quality requirements, v) commercialize the non-harmonised fertilisers in accordance with national law (Nutriman, 2022).

The new fertiliser regulation does not include legislation regarding general acceptance of recovered resources as ingredients in fertilisers. Compost and digestate from biowaste are mentioned as Component Material Categories (CMCs). Following the STRUBIAS initiative focussed on evaluating fertiliser use of e.g. struvite from wastewater treatment plants and materials from sludge ashes, in 2021 an additional 3 CMCs were added (Annexes II and IV to Regulation EU, 2019/1009, 2021): ‘Precipitated phosphate salts and derivates’, ‘Thermal oxidation materials and derivates’, and ‘Pyrolysis and gasification materials’. This is an important step in facilitating the closing of cycles between wastewater and agriculture. Still for many recovered resources the problem of their legal classification as waste (EurEau, 2021) is a hindrance to their acceptance and making use of their full potential in a circular economy.

3.7.4. *Potential strategies to overcome barriers*

With regard to non-technological strategies, the proposed decentralised nutrient recovery strategy requires a change in thinking from involved stakeholders and interested groups, considering not only technical but organisational, social and governance dimensions. To achieve these improved interactions, technology developers must work with social scientists to understand how technology users perceive issues related to implementation and usage of the technologies from the various perspectives of involved stakeholders. Moreover, it is important to promote social engagement with farmers, technology users and providers, citizens, civil society associations and government bodies. Other options, such as exploring the proposition of effective governance models that can ensure the implementation of nutrient recovery approaches at local level, can be of great aid. A possible strategy to overcome rejection against waste streams or obtained products could be avoiding streams that may cause rejection such as BW (others such as kitchen waste or manure have been widely used), although an important source of nutrients would be undervalued; and obtaining products that cause less social rejection (in general, solid fertilisers such as struvite, ammonium sulphate, CaP, PO_4 salts) versus digestate NPK fertiliser. In this case, pelletising the product would be a good option to increase its acceptability, but also facilitate its field application. Moreover, in several countries there are legal barriers for the adoption of resources recovered from wastewater. The use of sludge resulting from municipal wastewater treatment plants differs from one European country to another. Some countries, such as Belgium, Denmark, Spain, France and Ireland, use over 50% of the collected sewage sludge directly on agricultural land, while others, such as Greece, the Netherlands, Slovenia and Slovakia do not use sewage sludge in agriculture (Iticescu et al., 2021). To overcome these political barriers, the promotion of novel regulatory frameworks and governance within a circular economy approach, as well as recommendations on the modification of related legislation, must be carried out.

4. Conclusions

A wide range of technologies for nutrient recovery are available, with different Technology Readiness Levels (TRL). Innovative technologies have been developed in many research and development projects, aiming at optimising waste valorisation and nutrient recovery. Among them, AD (through -more or less- innovative processes and reactors) seems to be the first step required in the valorisation chain, generating energy in form of biogas. The solid fraction (hygienised) can be used as NPK fertiliser, directly or pelletised, or (if direct use is forbidden by local regulation), can be submitted to several processes to obtain P-based fertilisers such as P salts, CaP, H_3PO_4 and P_2O_5 ashes. The liquid fraction can also be valorised through diverse technologies, obtaining struvite and ammonium sulphate/nitrate, among other products, as well as reclaimed water for irrigation (after removing recalcitrant contaminants and disinfecting the effluent).

The selection of the most suitable technologies must be done considering their cost-efficiency, for which their evaluation under the same operational conditions is necessary. In this context, optimising reagent doses and electricity consumption are of crucial importance, as well as having high concentrations of N and P in the stream to be treated, for which technologies like Run4Life’s ultra-low vacuum toilets are of great relevance, allowing to obtain concentrated BW. The decentralised treatment of separated streams also favours the access to high concentrated streams, being an excellent strategy for nutrient valorisation. Another approach to maximise recovery is to implement a train of technologies, such as the ones depicted in Fig. 2 and Fig. 3.

It is also important to upscale, replicate and mainstream the decentralised valorisation of waste(water)s, for which many P- and N-rich waste streams are available, including sewage sludge, organic waste, agricultural waste, and agri-food industry wastewaters, among others. Moreover, mainstreaming waste valorisation necessarily comes with overcoming social barriers, for which promoting social acceptance among stakeholders and producing fertilisers with low associated rejection are of great importance.

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CRediT authorship contribution statement

Iemke Bisschops: Validation. **Elvira Serra:** Validation. **Nicolás Morales:** Project administration, Validation. **Gemma Torres-Sallan:**

Conceptualization, Data curation, Investigation, Methodology, Validation. **Natalia Rey-Martínez:** Investigation, Writing – original draft. **Sonia Sanchis:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing. **Eduard Borràs:** Validation. **Miriam H. A. van Eekert:** Validation.

Declaration of Competing interest

The authors declare no competing interests.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.clwas.2024.100139.

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