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Resource and water recovery solutions for Singapore's water, waste, energy, and food nexus

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Resource and water recovery solutions for Singapore’s water, waste, energy, and food nexus.

Part I: Resource recovery from wastewater and sludge.

Authors: Roujia Qiu, Jonathan Zhiquiang Lee, Laetitia Ingabire

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Colophon

Title	Resource and water recovery solutions for Singapore's water, waste, energy, and Food nexus. Part I: Resource recovery from wastewater and sludge.

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Summary

Singapore is a city-island-state in the transition towards a circular economy. The country has already implemented policies and adopted several approaches that contribute to closing loops for e-waste, packaging waste, and food waste. However, other areas that also contribute to a circular economy have not been fully explored in Singapore. One of these areas is resource recovery from wastewater streams.

In this report, we review state-of-the-art technologies to recover valuable components from domestic wastewater and sludge. These technologies are analyzed based on technological maturity and applicability for the recovery of phosphate, and organic compounds such as volatile fatty acids, bioplastics, and biomass. The report covers the current status of the recovery of these compounds in the Singaporean context and identifies factors that can promote or prevent the application of the recovery processes.

This review is part of a desk study in the Knowledge to Knowledge (K2K) activities of the PiB ReCirc framework and conducted by master's students from the National University of Singapore (NUS) and Wageningen University (WUR), supervised by Wageningen Food & Biobased Research (WFBR).

1 Introduction

1.1 Singapore, circular economy and resource recovery

Singapore is considered a city-state in the transition towards a circular economy with many opportunities for progress, which could serve as a model for other countries designing their circularity path [1]. Initiatives such as the Zero Waste Master Plan has been introduced to close e-waste, packaging waste, and food waste loops, and reduce per-capita waste landfilled by 30% by 2030 [2]. The Zero Waste Master Plan is complemented by the Green Plan, which is a multi-ministry effort to tackle climate change and co-create sustainable solutions with five pillars, i.e., city in nature, sustainable living, energy reset, green economy, and resilient future, collective action from the whole of society [3, 4]. Singapore has also adopted circular economy approaches for closing water loops by increasing water reuse [5]. The Public Utilities Board (PUB) makes sure that wastewater is collected and treated to international standards. The PUB produces ultra-clean reclaimed water under the brand name NEWater, and it currently supplies up to 40% of Singapore's water needs [6, 7].

An aspect, however, that has not been fully addressed when it comes to closing the water loop is resource recovery, other than water, from wastewater streams. The PUB has published a development roadmap for used water treatment, but it does not give details on the strategies and implementation of processes to recover valuable compounds [8]. So, the question is to what extent Singapore plans to recover compounds from wastewater and what strategies will be developed in the future. There is a wide variety of possible alternatives including commonly recovered compounds, such as water, energy, and nutrients, and emerging options, such as cellulose, biopolymers, bioplastics, and proteins [9].

In the present report, we look into the different technologies available to recover valuable components from domestic wastewater, specifically, phosphate, cellulose, volatile fatty acids (VFAs), and bipolymers. The report shows the analysis of these technologies according to not only their efficiency and technology readiness level (TRL) but also to their applicability and suitability to the needs and situation in Singapore.

The report aims to answer the following questions:

- What technologies are available to recover phosphate, cellulose, volatile fatty acids (VFAs), and biopolymers?
- What products can be produced from these components? What is the market potential of these products?
- What factors can promote or prevent the application of the recovery process in Singapore?

This report is the result of a desk study carried out by master's students from the National University of Singapore (NUS) and Wageningen University (WUR), supervised by Wageningen Food & Biobased Research (WFBR). The study is part of the activities conducted within a Knowledge to Knowledge (K2K) project in the PiB ReCirc framework. The study included the collection of information through a literature search and knowledge exchange sessions between the students

1.2 PIB ReCirc partnership framework

This study is part of one of the activities conducted within the Partners for International Business ReCirc program. Partners for International Business (PIB) is a program in which Dutch companies can realize their international ambitions in a public-private partnership. The ReCirc Singapore partnership aims to explore and exchange collaboration on circular solutions for waste processing, sludge, and resource recovery in Singapore and the Netherlands. The following organizations are part of the ReCirc Singapore partnership: Witteveen+Bos (cluster coordinator), Waternet, Amsterdam Institute for Advanced Metropolitan Solutions, Nijhuis Industries, Paques, CirTec, World of Walas, Asia Pacific Breweries, Organic Village, Blue Phoenix Group, KWR Watercycle Research Institute, Delft University of Technology, Wageningen University and Research, and Upp! UpCycling Plastic. The target topics addressed by the partnership are:

- Incinerated bottom ash and fly ash treatment and application as a building material
- Sorting, separating, segregating, and recycling urban waste
- Integrated recovery of renewable energy and resources from waste, used water, UWTP sludge
- Packaging and plastic waste management and treatment
- Food waste management, treatment, and resource recovery
- E-waste handling and recovery of valuable materials

Part of the activities promoted by the ReCirc partnership includes three Knowledge to Knowledge (K2K) projects. The present report is one of the outcomes of the third K2K project, which aims to identify the factors that are needed to accelerate i) the extraction of valuable components from wastewater and sludge and ii) the valorization of food waste. Previous K2K projects were focused on identifying opportunities for enhancing the circular economy in Singapore and the Netherlands through city blueprint frameworks (CBF) and a material flow analysis (MFA).

2 Phosphate recovery

Phosphate is one of the most common forms of phosphorus (P) in domestic wastewater. As the 11th most abundant element in the Earth's crust, P is an essential element for all living organisms. Phosphorus is a finite substance, whereby its function cannot be replaced by any other substance in biochemical processes. Today, mined phosphate rock is the main source of phosphate. However, global phosphate rock reserves are mainly located in a few countries such as Morocco, Iraq, and China [10]. Thus, over 90% of countries worldwide would need to rely on imported phosphate [11, 12].

Phosphate from mined phosphate rock is mostly used as fertilizer for agriculture. It can also be processed into food products, detergents, toiletries, and industrial chemicals. Despite a wide range of industrial uses for phosphate, the current use of phosphate is highly inefficient, especially in the agricultural industry. Phosphate leached from agricultural land has led to eutrophication problems of water bodies. Currently, large-scale phosphate recovery is not being practiced in Singapore. It was estimated that in 2012, 9.5% of Singapore's total phosphorus imports were directly lost to the environment and that phosphate loss is likely to increase in the future if current trends continue [11]. In this sense, phosphate recovery becomes an important way to reduce the risk of environmental deterioration.

2.1 Technologies for phosphate recovery

Phosphate can be recovered from either wastewater or sludge. In terms of mechanism, the technologies for phosphate recovery are divided into adsorption, ion exchange, precipitation, crystallization, wet chemical treatment, and thermal treatment. The related information about these phosphate recovery technologies is summarized in **Table 1**, including recovered compounds, operational scale, TRL, recovery efficiency (%), and technology providers.

2.1.1 Current industrial-scale processes

a. ANPHOS®

The ANPHOS® technology was developed by Colsen B.V., Netherlands. The ANPHOS® technology is a batch process, which consists of two process steps: stripping and reaction, **Figure 1**. In the stripping step, CO_2 is stripped from the wastewater, which results in a pH increase. The wastewater is then pumped to the reaction tank, where magnesium oxide (MgO) is added to the wastewater and the controlled struvite (mineral substance composed with magnesium ammonium phosphate, $MgNH_4PO_4{\cdot}6H_2O$ or MAP) formation process starts. In the reaction tank, struvite formed settles and is delivered to a dewatering or struvite recovery system.

It has been reported that with the removal of one kilogram (kg) orthophosphate, an amount of 0.45 kg ammonium nitrogen, as well as 1.3 kg of magnesium, is captured to generate 7.9 kg struvite. The recovery efficiency is in the range of 80~90% [13]. The ANPHOS® technology can be used for both industrial and domestic wastewater with P levels of > 50 mg/L.

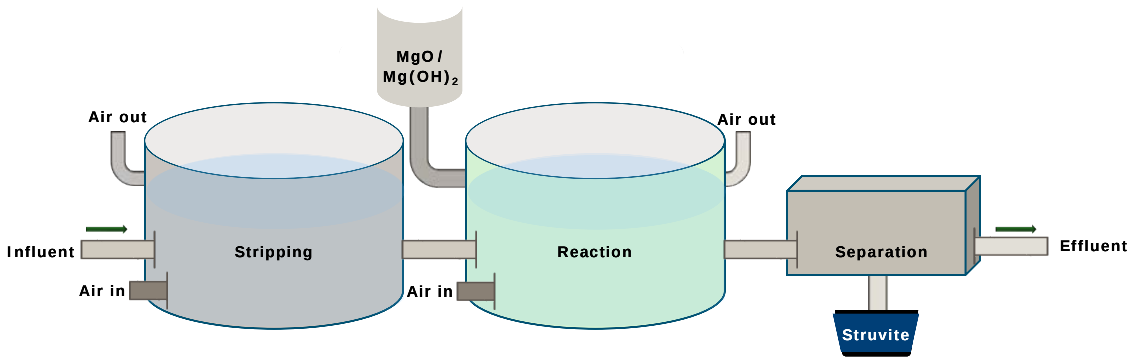

Figure 1 Schematic diagram of the ANPHOS® process. (Adapted from Ref. [14])

b. PHOSPAQ®

The PHOSPAQ® process developed by Paques B.V., Netherlands is applied to remove and recover phosphate from anaerobic and sludge digested effluents as struvite. The PHOSPAQ® process can take place in one aerated continuous stirred tank reactor (CSTR), **Figure 2**. As a result of aeration, the chemical oxygen demand (COD) is biologically converted into new biomass and CO_2. The process includes the addition of magnesium oxide (MgO), which promotes the precipitation of phosphate, and ammonium, as struvite at a pH of 8.2~8.3. A patented separator system at the top of the reactor is applied to retain the struvite into the system. Finally, the struvite is harvested from the bottom of the reactor using a hydro-cyclone, followed by a screw press, and transferred into a container. PHOSPAQ® is considered a cost-effective technology compared to the method of dosing iron salts to form iron phosphate (FeP) [15]. Moreover, the produced struvite granules are ready for agricultural use (fertilizer), which can be processed into slow-release fertilizer for N, P, and Mg. The struvite complies with European Union (EU) standards for fertilizer. The recovery efficiency of the PHOSPAQ process is 70~95% [16].

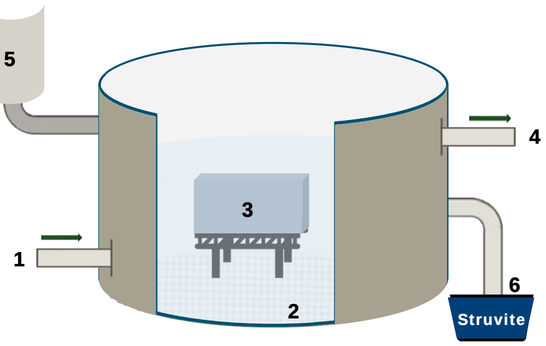

Figure 2 Operation principle of PHOSPAQ™ process. 1) Influent; 2) aerator grid for mixing; 3) separator for struvite retention; 4) effluent; 5) MgO dosing; 6) struvite harvesting. (Adapted from Ref. [15])

c. PhoStrip

The PhoStrip is a side-stream process of the biological phosphorus removal [17]. During biological phosphorus removal, microorganisms known as PAOs (polyphosphate, poly-P, accumulating organisms) store an excessive amount of phosphate, more than what is required for growth. Under aerobic conditions and limiting carbon sources, PAOs used up their intracellular carbon reserves to take up phosphate. On the other hand, under anaerobic conditions and with an excess of organic carbon in the environment, these microorganisms replenish their carbon reserves. The energy required to store carbon comes primarily from the hydrolysis of the intracellular poly-P [18], which in turn results in the release of phosphate to the environment. The PhoStrip process promotes the release of poly-P by adding a readily biodegradable organic source to the stripper tank (**Figure 3**), which is the heart of the process and functions as a standard sludge enricher and is normally used for the pre-thickening of the surplus sludge [19].

The phosphorus release occurs in a part of the return sludge. Phosphorus is recovered by lime precipitation to form calcium phosphate (CaP). The PhoStrip process can achieve 60% phosphorus recovery.

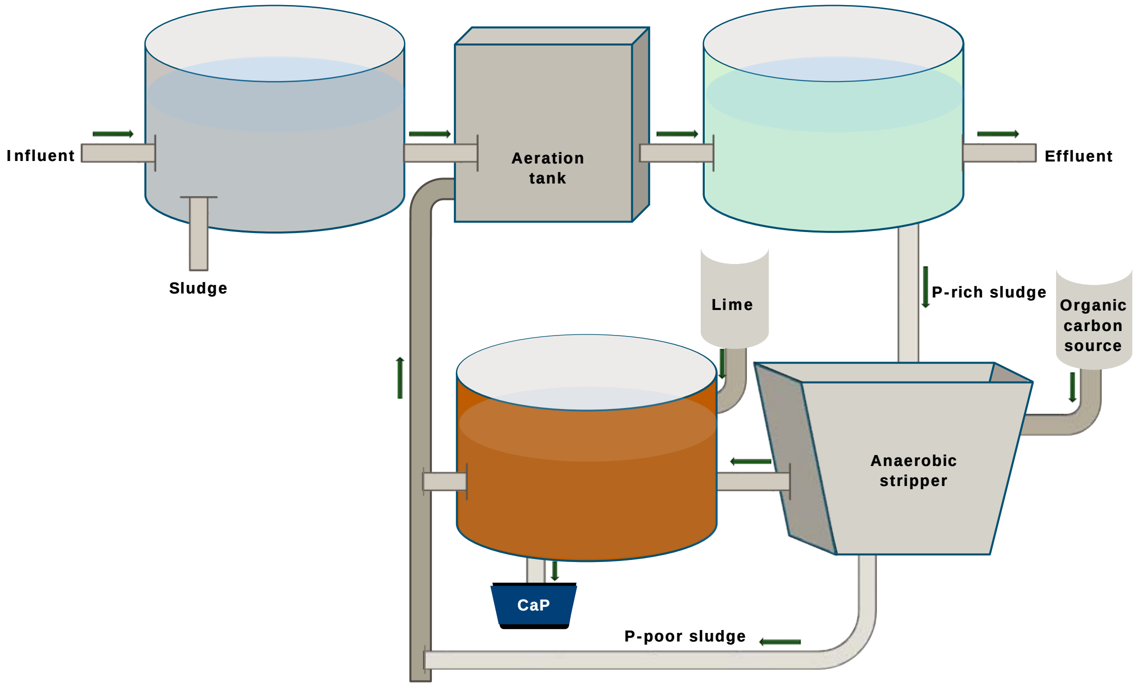

Figure 3 Schematic diagram PhoStrip process (Adapted from Ref. [20])

d. FIX-Phos

The fixation of phosphorus by the FIX-Phos process, which has been developed and patented by Technische Universitat Darmstadt, Germany, combines struvite prevention and phosphorus recovery. During the FIX-Phos process, calcium silicate hydrate (CSH) particles (a by-product from the production of gas concrete) are added to the sewage sludge during anaerobic treatment. The CSH fixates phosphorus as calcium phosphate and reduces the phosphorus concentration in the sludge water to control struvite formation. The phosphorus-containing recovery product can be separated and recovered from the digested sludge. In existing pilot plant experiments, when CSH at concentrations of 2~3.5 g/L was added to a mixture of primary sludge and waste activated sludge (WAS) from enhanced biological phosphorus removal (EBPR), 21~31% of phosphorus contained in digested sludge could be recovered. The recovery product contained a few heavy metals and a phosphorus content of 18 wt % P_2O_5, which allows for recycling as fertilizer. The fixation of phosphorus within the digester may increase the dewaterability of wastewater sludge. The phosphorus recycles stream to the headworks of the WWTP is reduced [21].

e. AirPrex®

The AirPrex® technology was developed and patented by the Berliner Wasserbetriebe after massive incrustations were found in the sludge dewatering lines of some WWTPs and downstream of anaerobic sludge digestion. This resulted in blockage of pipes and damage to pumps. Analysis of the incrustations showed that the precipitated material was mainly struvite with small portions of calcium phosphate [22]. The problem was solved by the AirPrex® technology for controlled precipitation of struvite with a recovery efficiency of 80~90% [16]. The AirPrex® process consists of aeration to strip CO_2 out and recirculating sludge, the addition of magnesium chloride ($MgCl_2$), struvite-crystallization and sedimentation, and struvite-separation and washing (**Figure 4**). This technology has been in full-scale operation in four WWTPs in Germany and the Netherlands [14].

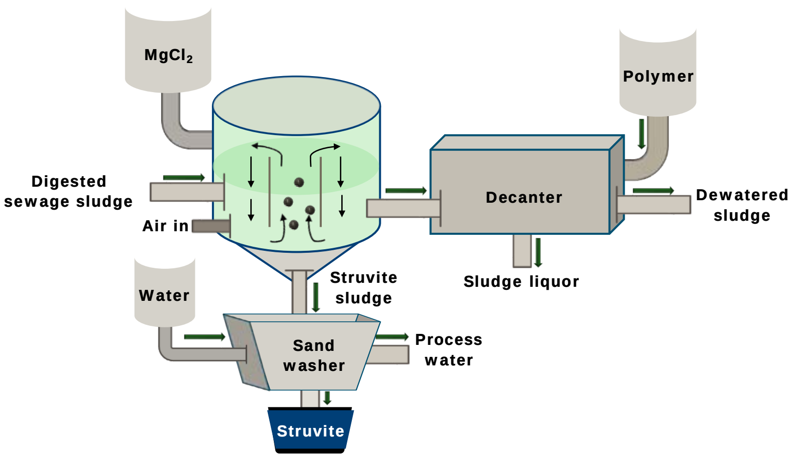

Figure 4 Schematic diagram AirPrex process (Adapted from Ref.[14])

f. NuReSys®

The NuReSys® technology developed by the Belgian company, Akwadok, stands for Nutrient Recycle System and is operated in two reactors. The NuReSys process differs from the ANPHOS® process because it is operated in continuous mode instead of batch mode at a lower residence time. Another difference with the ANPHOS® process is the use of $MgCl_2$ as a magnesium source and the addition of a 29% sodium hydroxide (NaOH) solution to the crystallization reactor instead of the use of MgO. The crystallization tank is equipped with a simple blade impeller. The optimal pH (8~8.5), reagent dosing, and mixing intensity can be guaranteed by a specifically developed and automated control algorithm. In this way novel crystalline matter grows upon existing crystals and unwanted impeller or reactor scaling can be prevented. The struvite pellets formed are removed by intermittent purging. The recovery efficiency is 85% [16].

g. Phosnix®

The Phosnix® process was developed in Japan by Unitika Ltd Environmental and Engineering Div. The Phosnix® process is a side-stream process that effectively removes and recovers phosphate from the digester wastewater of the sludge treatment process in WWTPs as granulated struvite. The wastewater is fed into the bottom of a fluidized bed reactor column. The column contains a bed of granulated struvite acting as seed material for crystal growth. Magnesium hydroxide ($Mg(OH)_2$) is added in a magnesium to phosphate ratio of 1:1, and the pH is adjusted to 8.2~8.8 with the addition of NaOH and by air stripping. The crystal retention time is 10 days so that the pellets can grow to a size of 0.5~1.0 mm. After that, the pellets are purged from the bottom of the reactor column. Fine granules of struvite in the separated liquid are recycled to the reaction column as new seed material to keep the continuity of the process [16].

h. Crystalactor®

DHV Water (The Netherlands) developed a crystallization process called Crystalactor® for the recovery of phosphorus with a recovery efficiency of 70~80%. The core of the Crystalactor® process is the pellet reactor partially filled with suitable seed material such as quartz sand, garnet, or small crushed pellets. By adding calcium, phosphorus crystallizes on the seed material in a fluidized bed at a pH of approx. 9, thus forming calcium phosphate [23]. The Crystalactor® technique is most suitable for treating flows with phosphate concentrations above 25 mg/L PO_4^{3-}-P. In municipal WWTPs, it can be used to treat a concentrated phosphate flow from EBPR.

i. Ostara Pearl® & WASSTRIP®

The Ostara Pearl® and WASSTRIP® technology were developed by Ostara Inc., Canada. The Ostara Pearl® technology is based on controlled chemical precipitation in an up-flow fluidized bed reactor that forms struvite in the form of highly pure crystalline pellets. The core of this process is the Pearl which can adapt to main- or side-stream operations to remove phosphorus from the treatment system. In the Pearl, the nutrient-rich feed streams (i.e., liquid fractions of sludge) are mixed with $MgCl_2$ and/or NaOH, and then fed into the reactor to form the struvite "seeds". These seeds grow in diameter until they reach the desired size of about 1~3.5 mm. Large struvite pellets (1.5~4.5 mm in diameter) are allowed to suspend at the bottom of the reactor, and the fine crystal nuclei will not be washed out from the top of the reactor. In a municipal WWTP, up to 90% of the phosphorus is removed from sludge dewatering liquid using this process. The resulting product is the highly pure fertilizer granules, which are marketed as a commercial fertilizer called Crystal Green®. The fertilizer can be used for any type of turf, field-grown nursery stock, and high-demand phosphorous crops. Besides, its solid property greatly reduces the risk of leaching or runoff from fertilizers [24].

Waste Activated Sludge Stripping to remove internal phosphorus (WASSTRIP®) is a value-add to Pearl providing critical benefits to anaerobic digestion facilities. WASSTRIP turbo charges nutrient removal and recovery, releasing phosphorus upstream before it reaches the digester. Therefore, the process protects digesters and equipment from struvite, improves dewaterability, and reduces biosolids [24].

j. Struvia

The Struvia technology is the precipitation of struvite with Mg^{2+} in sludge liquor after dewatering and pH increase by the addition of NaOH. It was developed by Veolia Water Technologies (VWT) Group to facilitate the recovery, valorization, and reuse of phosphorus in domestic wastewater and concentrated industrial and agricultural water as struvite crystals. This opens the way to local reuse of phosphorus, especially in agriculture [25].

k. Thermphos®

The Thermphos® (former Hoechst) technology is a thermochemical treatment of the sewage sludge ash (SSA) and is performed in quasi-closed systems (e.g., rotary furnaces). Based on this approach, sludge ashes are exposed to chlorine-containing substances, potassium chloride or magnesium chloride. At temperatures > 1,000°C, most heavy metals are turned into heavy metal chlorides and removed from sludge ashes as vapors with subsequent precipitation during flue gas cleaning. Potassium and/or magnesium phosphates are formed by applying the mentioned chlorides. After a subsequent specific dosage of nitrogen and/or potassium as well as the removal of heavy metals, various multi-nutrient fertilizers can be produced and then used in agriculture. Respective investigations were carried out within the frame of the EU research project" SUSAN–Sustainable and Safe Reuse of Municipal Sewage Sludge for Nutrient Recovery ". The recovery efficiency is higher than 90% [23]. The ThermPhos plant in Vlissingen, the Netherlands, went bankrupt and is demolished.

2.1.2 Pilot-Scale processes for future technologies

a. RECYPHOS

Phosphorus recycling-sustainability contribution at the decentralized wastewater treatment (RECYPHOS) is a concept for small WWTPs. The technology consists of a precipitation process carried out in a fixed-bed reactor. The product produced is FeP, whic needs to be further treated because it cannot be directly used as fertilizer [26]. RECYPHOS is a modular technology intended that can be integrated in new and in existing WWTPs [27].

b. IEX

Cranfield University has developed a tertiary nutrient removal and recovery technology based on ion exchange (IEX) processes. After secondary treatment, ammonia and phosphate are selectively removed from the wastewater with specific IEX media. The capacity of the IEX media is regularly restored by regeneration solutions, where the nutrients are accumulated. With an ammonia stripper or a combined precipitation and filtration process, the nutrients are removed as products from the regenerants. Multiple uses of the regenerants and high recovery efficiencies are key aspects of the technology to ensure economic feasibility and sustainably. The recovery efficiencies are up to 97% for ammonia and 95% for phosphorus. The recovered products are ammonia solution and calcium phosphate salts, which can be directly re-used in the chemical and fertilizer industries [28].

The overall IEX technology was operated as the demonstration plant fed with 10 m^3/day of secondary effluent at the Cranfield University pilot-hall, including 1 micro-screen filtration for secondary effluent solids removal, 1 ion exchange process for ammonia removal with MesoLite media, 1 ion exchange process for phosphorus removal with hybrid ion exchange media (HAIX), regenerant storage tanks (NaCl and NaOH), regenerant rinse water tanks and nutrient recovery processes. The liquid-liquid membrane process was used for ammonia recovery, producing ammonium sulfate, and a mixing tank and a filter were used for phosphate recovery as calcium phosphate (hydroxyapatite) [28].

c. PRISA

The PRISA Process begins with acidification of the raw sludge from EBPR with phosphate dissolution in a reactor. Then the raw sludge is separated from the supernatant. A major part of the phosphate, biologically bound as well as a smaller part of the dissolved phosphate from the hydrolysis of biomass, is contained in the supernatant. That is, over 40% of the phosphorus load from the raw wastewater is concentrated in this separated stream. This stream is then mixed and struvite forms in the precipitation reactor by adding MgO [29].

d. P-RoC®

Phosphorus recovery by crystallization from waste- and process water (P-RoC®) is a patented technology that was developed by the Karlsruhe Institute of Technology, Germany. It can recover phosphorus from fluids containing a reactive substrate without chemicals, and it is conducted in a semi-continuous stirred reactor by adding tobermorite-rich CSH compounds [30]. The P-RoC® technology is easy to handle and adopt in wastewater treatment. About 80% of soluble phosphorus can be recovered via this technology [23]. The generated secondary phosphate can be processed in the phosphate industry or used as fertilizer without further treatment. The content of the pollutants in the products is much lower than the limiting values of the fertilizer regulations [31].

e. PASH

The phosphorus recovery from Ash (PASH) process was developed at the Institute of Applied Polymer Science (IAP), Aachen University, Germany. The process recovers phosphorus as calcium phosphate from incinerated SSA. It utilizes a liquid extraction method after leaching hydrochloric acid (HCl) to remove both heavy metals and iron through filtering. 90% of phosphorus recovery can be achieved by solubilizing phosphorus with HCl (8%) at a retention time of 60 minutes. The filter cake is washed with water and then dewatered to help remove as much phosphorus as possible. The liquid filtrate (mixed with the water from the dewatered sludge cake) contains phosphorus, calcium, and other metals. This filtrate is thus treated by solvent extraction to recover selected metals, followed by phosphate precipitation. If the aluminum content of the leaching solution is very high, pH should be adjusted to 2 to precipitate aluminum phosphate which can be removed easily. At pH 3.6, calcium phosphate precipitates by adding lime to the solution with a reaction time of 15 minutes. The phosphorus content is 16%. Capital expenditure (CAPEX) costs and operating expenditure (OPEX) costs for this system per year are estimated to be €5,000,000 and €4,000,000, respectively. The first full-scale plant has a design capacity to treat 30,000 tonnes/year of sludge ash and aims to recover 700 tonnes/year of phosphorus [32].

f. CAMBI/KREPRO

The KREPRO process is designed to hydrolyze digested sludge by acids at high temperatures and high pressure. Phosphorus is recovered as FeP with a recovery efficiency of 70%. The process has been operated on a pilot-scale in Helsingborg, Sweden, and was close to a full-scale application in Malmo, Sweden, but was canceled due to the new goals from the first evaluation from the Swedish environmental protection agency (EPA) [33, 34].

g. LeachPhos®

The LeachPhos® process is a wet-chemical extraction process with diluted mineral acid from sewage sludge ash [35]. Calcium phosphate is produced by this technology, with recovery rates of 60-70% relative to the WWTP influent [36]. Heavy metals can be partly removed from the product by the leaching and precipitation steps.

h. EcoPhos

EcoPhos S.A. has developed a modular process for the valorization of low-grade phosphate rock and/or various alternative phosphate resources based on soft digestion by hydrochloric/phosphoric acid. The process is flexible and can use several types of raw materials by the modular setup to produce a variety of products (e.g., fertilizer-, feed- and food-grade phosphoric acid, animal feed (DCP and MCP), and liquid NPK, PK, and NP fertilizers). The process has economic and ecological advantages compared to conventional industrial processes and those in development for the valorization of SSA, as it is simple, stable, and easy to control without using expensive chemicals, raw materials, and equipment. The performance has been tested in industrial plants in Bulgaria, Syria, and Peru, as well as a pilot- and lab-scale installations. Uptime longer than 7,800 hours/year is demonstrated and the yield on P_2O_5 is 90% or higher, but the process may overuse HCl when manufacturing products such as isocyanate, caustic soda, or potassium sulfate.

The process can also produce uranium (U)-free fertilizers, while conventional fertilizers generally contain 300~500 mg U/kg P_2O_5. Furthermore, most of the by-products including high-purity $CaCl_2$, radiation-free gypsum, silicate filter residue, and Fe/Al-chlorides, can be split into sellable products to minimize final waste by applying different modules [12].

i. AshDec®

The AshDec® process utilizes chloride dosage and thermal treatment (> 900 °C) to produce P or PK fertilizers with relevant mass fractions of silicates and sodium [37]. The process can use various inlet streams, e.g., animal by-products and other nutrient-rich organic waste, including SSA [37].

j. Mephrec

The Metallurgical Phosphorus Recovery (Mephrec) process was developed by the German company Ingitec. The process recovers phosphorus and energy from dried sludge briquetted with slag-forming substances and coke. The mixture is treated at 2,000°C, transferring phosphorus into the mineral slag and heavy metals to liquid phase (Fe, Cu, Cr, Ni) or gaseous phase (Hg, Cd, Pb, Zn). The silico-phosphates containing slag is separated from the metal phase after being tapped at 1,450°C. The final product contains 4.6~12% P_2O_5 (varied by mixing sewage sludge with animal meal) with over 90% citric acid solubility. With SSA, the P_2O_5 content can reach 20%, but energy recovery is not possible. The process has been tested in a pilot plant with a capacity of 8 tonnes/hour briquettes, and a feasible process should have a minimum capacity of 40,000 tonnes/year briquettes [38].

k. ViviMag

With this technology, phosphate precipitates in the form of vivianite ($Fe_3(PO_4)_2 \cdot 8H_2O$) and can be recovered from anaerobically digested sludge [39]. The technology takes advantage of the paramagnetic properties of vivianite to recover it using magnetic separations. At the lab scale, it has been shown that about 50-60% of vivianite can be recovered [40]. The entire process relies on the application of high doses of iron to increase the conversion of P in the sludge into vivianite during anaerobic digestion [41]. The technology has been developed and implemented at the pilot scale in the Netherlands [39].

Table 1 Phosphate recovery technologies

Phosphate recovery technologies		Target	Recovered compounds	Operational scale	TRL	Recovery efficiency (%)	Companies
Adsorption	RECYPHOS	EBPR sludge liquor	Iron phosphate (FeP)	Pilot-scale	6	-	Department of Water Chemistry, TU Dresden; Department of Water Technology and Sanitary Engineering, BTU Cottbus
Ion exchange	PHOSIEDI	EBPR sludge liquor	Calcium phosphate (CaP)/phosphoric acid	Lab-scale	5	-	Universität Karlsruhe (TH); Institut für Wasser und Gewässerentwicklung (IWG); Bereich Siedlungswasserwirtschaft
	IEX	Secondary effluent	CaP	Pilot-scale	-	95	Cranfield University, UK
	BIOCON	Mono-incinerated sludge ash	Phosphoric acid	Lab-scale	6	-	Royal Institute of Technology, Sweden
Precipitation	ANPHOS®	Anaerobically digested wastewater	Struvite	Industrial-scale	9	80~90	Colsen B.V., Netherlands
	PHOSPAQ®	Anaerobic and sludge digested effluent	Struvite	Industrial-scale	8	70~95	Paques B.V., Netherlands
	PhoStrip	EBPR sludge liquor	Struvite/CaP	Industrial-scale	-	60	Phostrip Abwasser Technik GmbH, Netherlands
	PRISA	EBPR sludge liquor	Struvite	Pilot-scale	6	40	Institute of Envrionmental Engineering of RWTA Aachen University, Germany

Table 1 Phosphate recovery technologies (cont.)

Phosphate recovery technologies		Target	Recovered compounds	Operational scale	TRL	Recovery efficiency (%)	Companies
Precipitation	Stuttgart process	Digested sewage sludge (both EBPR and chemical sludge)	Struvite	Lab-scale	6	-	University of Stuttgart, Germany
	FIX-Phos	Anaerobically digested EBPR sludge	CaP, CaP on CSH	Industrial-scale	-	21~31	Technische Universitat Darmstadt, Germany
	Airprex®	Anaerobically digested EBPR sludge	Struvite	Industrial-scale	9	80~90	Berliner Wasserbetriebe, Germany; CNP-Technology Water and Biosolids GmbH, Germany
	ViviMag	Anerobically digested sludge	Vivianite	Pilot-scale	6	-	Wetsus and Kemira, the Netherlands
Crystallization (i.e., pellets)	NuReSys®	Anaerobically digested EBPR sludge	Struvite	Industrial-scale	9	85	NuReSys/Akwadok BVBA, Netherlands
	Phosnix®	Anaerobic digestion effluent	Struvite	Industrial-scale	9	90	Unitika Ltd, Japan
	Crystalactor®	EBPR sludge liquor	CaP	Industrial-scale	9	70~80	DHV Water B.V., Netherlands
	Ostara Pearl® & WASSTRIP®	EBPR sludge liquor	Struvite	Industrial-scale	9	85	Universisty of British Colombia/Ostara, Canada
	P-RoC®	EBPR sludge liquor	CaP, CaP on CSH	Industrial-scale	6	-	Karlsruhe Institute of Technology, Germany
	Struvia (modified PhoStrip)	EBPR sludge liquor	Struvite	Industrial-scale	7	-	Veolia Water Technologies (VWT) Group, Japan

Table 1 *Phosphate recovery technologies (cont.)*

Phosphate recovery technologies		Target	Recovered compounds	Operational scale	TRL	Recovery efficiency (%)	Companies
Wet chemical treatment (i.e., hydrolysis, leaching)	Seaborne®	Digested sewage sludge (EBPR)	Struvite/ hydroxyl apatite	Industrial-scale	7	>90	Seaborne Environmental Research Laboratory, Germany
	PASH	Mono-incinerated sludge ash	Struvite/CaP	Pilot-scale	6	80	MEAB Chemie Technik GmbH, Germany
	CAMBI /KREPRO	Digested sewage sludge (both EBPR and chemical sludge)	Phosphoric acid	Pilot-scale	6	-	Heisingborg WWTP, Sweden
	LeachPhos®	Mono-incinerated sludge ash (both EBPR and chemical sludge)	CaP/struvite	Pilot-scale	6	70.1	BSH Umweltservice AG, Switzerland
	SEPHOS	Mono-incinerated sludge ash (both EBPR and chemical sludge)	CaP	Lab-scale	6	-.	Technische Universitat Darmstadt, Germany
	SESAL-PHOS	Mono-incinerated sludge ash (both EBPR and chemical sludge)	CaP	Lab-scale	6	-.	Technische Universitat Darmstadt, Germany
	EcoPhos	Mono-incinerated sludge ash (both EBPR and chemical sludge)	Phosphoric acid, dicalcium phosphate	Pilot-scale, full plant planned	7	97	EcoPhos S.A., France

Table 1 Phosphate recovery technologies (cont.)

Phosphate recovery technologies		Target	Recovered compounds	Operational scale	TRL	Recovery efficiency (%)	Companies
Thermal treatment	Ash Dec®	Mono-incinerated sludge ash (both EBPR and chemical sludge)	Calcined phosphates ($CaNaPO_4$)	Pilot-scale, full plant planned	7	98	Outotec/BAM, Austria
	Mephrec	Mono-incinerated sludge ash (chemical sludge)	Silico-phsphates	Pilot-scale, full plant planned	7	80.5	Ingitec GmbH, Germany
	Thermphos®	Mono-incinerated sludge ash	P_4	Industrial-scale	9	>90	Thermphos, Netherlands
Use of bacteria	BIOLEACHING	Digested sewage sludge	Struvite	Lab-scale	6	-	Georg Fritzmeier GmbH & Co. KG, Germany
Low pressure acid oxidation, membrane phosphate separation	LOPROX /PHOXAN	N.A.	Phosphoric acid	Lab-scale abandoned	6	-	RTWH Aachen University, Germany
Super critical water oxidation	Aqua Reci®	Digested sewage sludge (both EBPR and chemical sludge)	CaP	Pilot-scale, abandoned	6	-	Feralco AB, Sweden

2.2 Market potential for recovered phosphate

Recovered phosphate, which is mostly in the forms of struvite, calcium phosphate, tetra phosphorus (P_4), FeP, and phosphoric acid, can be used to produce slow-release fertilizers for agriculture and supply the secondary phosphate industry [42, 43]. It is essential to identify the pricing, demand, quality, storage, transportation, and distribution of recovered phosphate with respect to the existing regulatory framework of contaminants and eco-toxicity for the development of its market strategy [43].

The recovered phosphate products would have market values as fertilizers, but their utilization would depend on local legislation and policy and incentives provided by local authorities. The phosphate price is influenced by the quality, demand, and capacity of the phosphate industries as well as the politics and speculation at the stock market [23]. For this reason, the market price of struvite has varied from 188 €/tonne to 763 €/tonne in recent years [43].

However, phosphate recovery from domestic wastewater is not competitive in terms of production costs in the short run. Without considering the possible operational savings or revenue from recovered phosphate, the costs of phosphate recovery from the liquid phase, sludge, and sludge ash were €9,000~15,000, €2,000~2,500, and €2,600~7,500 per tonne recovered phosphorus, respectively [21]. These production costs are higher than the market values of recovered phosphate products. But in the long term, phosphate recovery will be economically feasible when external benefits (e.g., environmental benefits, increase in resource availability, and government incentives) are taken into account [43-45].

2.3 Current practices to recover phosphate from wastewater in Singapore

The total phosphorus (TP) concentration in the influent wastewater of the Ulu Pandan Water Reclamation Plant (UPWRP), the second-largest municipal wastewater treatment plant (WWTP) in Singapore with a total treatment capacity of 361,000 m^3 per day, is in the range of 5.2~8.1 mg/L and relatively low [46]. Thus, it may not be economically feasible to implement phosphate recovery from domestic wastewater.

Currently, research on phosphate recovery in Singapore is being carried out, for example at a lab scale (**Table 2**). Nanyang Technological University, Singapore (NTU) investigated the feasibility of using seawater, brine, and $MgCl_2$ as low-cost magnesium sources for struvite formation, and the optimal conditions to induce struvite precipitation in hydrolyzed urine, synthetic and real urine samples in bench-scale batch experiments. The results showed that the phosphorus recovery efficiency increased with the molar ratio of magnesium and phosphorus (Mg/P) and that the calcium in the magnesium sources could affect the purity of the struvite product. Overall, more than 95% of the total precipitate mixture formed in all conditions is struvite, which makes the mixture more beneficial as fertilizer in practical application. The outcomes of this project can be used for the development of phosphate recovery at an industrial scale [47, 48].

Qiu and Ting [49] reported a novel approach to recover phosphorus from domestic wastewater via an osmotic membrane bioreactor (OMBR). The OMBR system collected activated sludge from the membrane bioreactor (MBR) at the UPWRP, Singapore as the inoculum and used synthetic wastewater (with COD, NH_4^+-N, and PO_4^{3-}-P concentration of about 700 mg/L, 60.0 mg/L, and 8.0 mg/L, respectively) as feed. In this system, the forward osmosis (FO) membrane rejected 98% of PO_4^{3-}-P and enriched it within the bioreactor. PO_4^{3-}-P of >95% was recovered from the supernatant of the bioreactor through amorphous calcium phosphate (ACP) precipitation under pH of 9.0 (adjusted by NaOH addition and/or CO_2 stripping), and the phosphorus content in the recovered solids was higher than 11.0%. In principle, this process could recover almost all the phosphorus, except that assimilated by bacteria for growth. The overall phosphorus recovery efficiency was about 50%.

Qiu et al. [50] further improved the OMBR system into the MF-FOMBR system for direct phosphorus recovery from domestic wastewater in the course of its treatment. The system was operating with raw domestic wastewater and activated sludge (as inoculum) collected from the MBR of the UPWRP, Singapore. In the process, a FO membrane (rejecting nutrients and resulting in their enrichment) and a microfiltration (MF) membrane (extracting nutrients) were run in parallel in a bioreactor. Phosphorus was thus recovered from the nutrients enriched MF permeate by precipitation without adding an external source of calcium or magnesium. The precipitates were mainly ACP with a phosphorus content of 11.1~13.3%. >90% phosphorus recovery can be achieved at pH 9.0, and the overall phosphorus recovery efficiency was 71.7% over 98 days.

Lefebvre et al. [51] investigated the phosphate (PO_4^{3-}-P) recovery from concentrate fraction of urine (80% of evaporation in volume) by adding MgO to induce struvite formation. The study showed that a 94% reduction of PO_4^{3-}-P concentration was achieved at the optimal Mg/N molar ratio (1:1). A potential benefit of 0.9 €/m^3 of concentrate or 0.2 €/m^3 of raw urine could be derived from struvite recovery, estimated based on a MgO cost of 150 €/tonne and a struvite value of 250 €/tonne (irrespective of capital and operational costs).

A processing system modeling framework for comprehensively evaluating phosphate recovery approaches in terms of both economic and environmental impacts was also developed by the Department of Chemical Engineering, Imperial College London, and Nanyang Environment and Water Research Institute, NTU. This framework was applied to design, simulate and analyze the treatment pathways to select the most suitable methods for P removal and recovery. The results suggested that ion exchange had the best P selectivity (100% P-elimination) in terms of economic performance; chemical approach to P removal was the best, followed by ion exchange; biological methods had significantly higher associated costs per unit P removed with an inferior environmental performance [52].

Compared with domestic wastewater, the concentration of P in some industrial wastewater streams is higher (**Table 3**), especially those from the food and beverage industry, and therefore these streams have higher phosphate recovery potential. In 2017, the food manufacturing industry contributed S$4.3 billion (i.e., 1.1% to Singapore's GDP) and thus the wastewater in this industry could be a source for phosphate recovery. Also, the phosphate recovery from industrial wastewater could be in line with Singapore's drive to recycle and reuse industrial wastewater, which is described in Section 4.1, as a synergy to increase the value proposition of industrial water solutions.

Besides, with the frequency and intensity of eutrophication events increasing in recent years, Singapore is also considering phosphorus management to reduce the P loss. Pearce and Chertow (2017), along with the urban planning agency of Singapore, have provided some scenarios (e.g., composting, separated incineration of organic and non-organic waste, anaerobic co-digestion of food waste and wastewater sludge and biomass co-generation, etc.) for sustainable solid waste and wastewater management, which serve as a support for an absolute reduction of phosphorus flows into the environment. One example of this is that the Singapore national water agency PUB and the National Environment Agency (NEA) have started the plan of anaerobic co-digestion of food waste and wastewater sludge by constructing the “Tuas Nexus”, which comprises the Integrated Waste Management Facility (IWMF) and Tuas Water Reclamation Plant (TWRP). Singapore generates about 1822 tonnes of food waste every day and there is a huge potential for biogas production [53]. The anaerobic co-digestion of food waste and wastewater sludge in “Tuas Nexus” will increase biogas production by 40% at the TWRP, compared to biogas yield from traditional treatment [54].

Table 2 Phosphate recovery practices applied in Singapore

Phosphate recovery technologies	Target	Recovered compounds	Recovery efficiency	Operational scale	References
Seawater-induced struvite precipitation	Synthetic and real urine after complete urea hydrolysis	Struvite	>99% (Mg/P molar ration of 1.1)	Lab-scale	[47]
Precipitation/crystallization in OMBR (NaOH addition and CO_2 stripping)	Synthetic wastewater	ACP, struvite	50% (overall)	Lab-scale	[49]
Precipitation/crystallization in MF-FOMBR (NaOH addition)	Raw municipal wastewater	ACP	71.7% (overall)	Lab-scale	[50]
Seawater-induced struvite precipitation	Synthetic urine	Struvite	50%~98% (Mg/P molar ratio=0.5:1~1.1:1)[a]	Lab-scale	[48]
MgO-induced struvite precipitation	Urine collected from prototype urine-diversion dehydration toilet	Struvite	94% (80% of urine evaporation in volume, Mg/N molar ratio=1:1)	Lab-scle	[51]
Chemical and ion-exchange approaches studied deliver sustainable advantages over biological pathways, both economically and environmentally, with each possessing different strengths.					[52]

[a] A complete P-recovery could be achieved only when the Mg/P molar ratio ascended beyond 1.1:1.

Table 3 Average concentrations of phosphorus in industrial wastewater

Industrial wastewater	*TP concentration (mg/L)*	*References*
Pulp and paper industry	0.02~36	[55]
Textile industry	<10	[56]
Winery	2~280	[57]
Dairy	9~132	[58]

3 Cellulose recovery

Cellulosic material in toilet paper is one of the major organic components in the influent of municipal WWTPs. The influent cellulose contents account for approximately one-third of the total suspended solids (TSS). The removal of cellulose requires two steps - hydrolysis and metabolism. The key step is biological hydrolysis. This process is heavily dependent on the temperature and sludge retention time. Unfortunately, conditions and results in the studies related to biological hydrolysis of cellulose are not easy to compare, because the effects of removal or biodegradation of cellulose on the oxygen demand, sludge production, nutrient removal, and dewaterability are still unclear [59-61]. The complex process of cellulose hydrolysis makes cellulose removal from wastewater energy-intensive and costly.

At the same time, cellulose is of great potential as one of the most recoverable products from wastewater flows, which could be recovered easily from wastewater by sieving [59, 61]. In other words, cellulose recovery would be a better choice than cellulose removal in WWTPs in terms of technical feasibility. The main properties such as biocompatibility, biodegradability, thermal and chemical stability make cellulose worth recovering. Many potential applications could be derived from cellulose recovery including as a reused secondary raw material, as a reinforcing component in binder-based materials in engineering applications. Besides, cellulose can also be processed into valuable molecules, building bio-blocks, bioplastics, and flocculants [62, 63].

3.1 Technologies for cellulose recovery

The most effective way to recover cellulose is by sieving the wastewater by a screen. Several companies in the Netherlands have developed fine screen technologies that use the rotating belt filter to sieve the wastewater and then acquire the cellulose sludge. The cellulose recovery technologies are shown in **Table 4**.

a. Fine-screen Technology

The Fine-screen Technology was developed by Brightwork B.V., Netherlands. In this process, a filter cake is formed on the rotating sieve belt of the fine screens to remove even smaller particles than the pore size (0.35 mm) of the sieve belt. Thickening takes place on the horizontal part of the sieve belt and after that, the filter cake drops into the internal dewatering press of the fine screen. About 60~80% of cellulose fibers (depending on the influent composition) are contained in the screenings. This technology has been applied in the Project of “Cellulose Assisted Dewatering of Sludge (CADoS)”, where the cellulose from domestic wastewater is removed and subsequently used for dewatering of biological sludge. Generally, waste-activated sludge (WAS) which is extracted from the return sludge stream will be thickened conventionally. In the CADoS system, this sludge is also withdrawn from the aeration tank and pumped to the internal dewatering press of the fine screen [64].

The special feature of CADoS is that it happens in practice under close cooperation between government, knowledge institutes, and industry and the support of the customer. The CADoS Project proves the feasibility of the fine-screen technology, and it is also applicable for other water boards. CADoS has some significant advantages: (1) The higher organic content in the dewatered sludge from CADoS generates more biogas; (2) The sludge volume to be transported and CO_2 emissions are reduced; (3) The use of polyelectrolyte and other chemicals will be limited to a significant extent; and (4) The energy required for aeration decreases with about 15% by removing organic material before biological treatment [64].

b. Cellvation®

The Cellvation® technology developed by CirTec B.V. and KNN Cellulose BV is a dynamic sieving process that separates the cellulose from the incoming wastewater during primary treatment and turns it into clean cellulose fibers. It demonstrates the technical feasibility of cellulose recovery and the potential of this new technology to contribute to a circular economy in the water sector.

Domestic wastewater enters the treatment plant and flows through a coarse screen that removes large particles (e.g., sand and stones). After that, the Cellvation® process starts when the wastewater is pumped through a grit chamber to remove the easily sinkable solids by gravity settling. The remaining wastewater goes through the cellulose washer that separates the cellulose fibers from hairs and other organic contaminants. The wastewater is then fed to a salsnes Filter, which is a rotating belt filter working by a rotating filter cloth and thus creating an endless filter. The filtrate is discharged, and the solids are removed from the filter utilizing a patented cleaning system that uses air pressure at the end of the filtration area. The cellulose fibers recovered from the rotating belt filter are pre-dewatered in the dewatering unit coupled to the filter and are further dewatered by the CellPress®. The sievings leaving the CellPress® are sterilized to ensure that the recovered product is clean and safe to use [65].

The benefits of Cellvation® technology include (1) Reduction of energy consumption for aeration by up to 20% and the increase of treatment capacity at WWTPs due to reduction of organic load in the activated sludge process; (2) Reduction of sludge volume which leads to lower polymer use for dewatering and lower sludge disposal costs; and (3) Recovery of a high-quality product: clean cellulose for reuse in road construction (e.g., as an additive in asphalt) or as a raw material for bio-composites and other buildings materials [65].

Table 4 Cellulose recovery technologies

Technology	Recovered products	Operational scale	TRL	Recovery efficiency (%)	Companies
Fine-screen Technology: sieve belt with a pore size of 0.35 mm	Cellulose fibers: filter aid for effective dewatering of biological sludge; fertilizers; raw material for reuse (e.g., bioplastics or board)	Pilot-scale, full plant planned	-	60~80	Brightwork B.V., Netherlands
Cellvation®: sieve belt with pore size ≤ 0.35 mm (e.g., 0.21 mm, 0.35 mm)	Recell®: biocomposite; bio-based chemical; asphalt additive	Pilot-scale, full plant planned	7	-	Cirtec B.V., Netherlands; KNN Cellulose B.V., Netherlands

3.2 Market Potential for recovered cellulose

The various existing market possibilities and market price ranges for the commercialization opportunities of recovered cellulose are summarized in **Table 5**. Overall, cellulose recovery is less economically feasible when used in the paper and carton industry because of hygiene issues. The recovered cellulose would be more suitable for use in construction and bioenergy. The market prices and sizes depend on the end-use of products which varies with the quality and properties of recovered cellulose. For instance, the feasibility of using recovered cellulose as pulp, paper, and board relies on its brightness, tensile and tear, freeness, and write-ability. Polymeric cellulose requires higher chemical purity. Meanwhile, building materials produced by recovered cellulose should meet the market requirement for strength, moisture absorbency, and fire resistance. It is necessary to thoroughly study the extraction and purification methods of cellulose and assess its feasibility to conform to the market criteria for all possible applications [43].

The application of recovered cellulose mainly falls into 8 categories: (1) filter aid for effective dewatering of biological sludge; (2) secondary raw materials for the textile and paper pulp industry; (3) reinforcing component in binder-based materials in the construction sector; (4) adsorbent for the removal of pollutants (e.g., oil, dyes, heavy metals, and ionic compounds) in wastewater treatment; (5) refinement into nano-cellulose; (6) soil conditioner; (7) fuel for biomass combustion plants; and (8) feedstock for the fermentation industry and bioethanol production [42, 43, 59, 61, 62].

The cellulose recovery from wastewater has not been implemented in Singapore up to now. According to the leading toilet paper supplier Asia Pulp and Paper Group (APP), the domestic demand for toilet paper in Singapore is about 28 million rolls a month, or about five rolls per person, indicating Singapore's great consumption of toilet paper and thus cellulose could have high recovery potential. However, it is questionable whether the cellulose recovery could be implemented due to the high maintenance costs.

Currently, the research on cellulose recovery in universities and research institutes is mostly focusing on other sources such as waste paper and soya bean (okara) residue. A research team from the NUS Faculty of Engineering had successfully converted paper waste into green cellulose aerogels which are non-toxic, ultralight, flexible, extremely strong, and water repellent [66]. This new material can be applied to oil spill cleaning, heat insulation, and packaging, and potentially used as coating materials for drug delivery and as smart materials for many biomedical applications. Nanyang Technological University Food Science and Technology (NTU FST) had developed green extraction technology to extract cellulose from the remaining solid residues after fermentation, and developed biodegradable packaging materials in 2017 [67]. This method adds a compound found commonly in detergent to okara to remove the lipids and proteins contained in the residue and thus leaves behind only cellulose which can then be used to create packaging materials. Although these technologies are not associated with cellulose recovery, the green cellulose aerogels and the biodegradable cellulose packaging materials indicate the market possibilities for recovered cellulose.

Table 5 Market possibilities and market price range for recovered struvite and cellulose [43].

Product	Market possibilities	Price range (€/tonne)
Cellulose	Textiles	1200~1900
	Non-woven	200~400
	Wood, timber	450~600 €/m^3
	Pulp, paper, and board	450~650
	Cellulose dissolving pulp	1600~2000
	Cellulose films	3000~3500
	Building materials (e.g., asphalt additive)	N.A.
	Cellulose fibre composites	200~400
	Green chemicals	50~100

3.3 Current practices to recover cellulose from wastewater in Singapore

The recovery of cellulose from wastewater has not been implemented in Singapore up to now. According to the leading toilet paper supplier Asia Pulp and Paper Group (APP), the domestic demand for toilet paper in Singapore is about 28 million rolls a month, or about five rolls per person, indicating Singapore's great consumption of toilet paper and thus cellulose could have high recovery potential. However, it is questionable whether the cellulose recovery could be implemented due to the high maintenance costs.

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4 Volatile fatty acids (VFAs) and biopolymers (PHAs, polyhydroxyalkanoates) recovery

Volatile fatty acids (VFAs) are short-chain fatty/carboxylic acids produced when organic matter is hydrolyzed and fermented, producing acetic, propionic, butyric, and other acids in smaller amounts. These compounds are produced commercially with petrochemical feedstocks and are important inputs in the pharmaceutical, petrochemical, food, cosmetics, tanning, and chemical industry [68]. The global VFA market is expected to be valued at US$122.7 billion in 2025 with a compound annual growth rate (CAGR) of 1% [69]. In addition, the bulk unit price of industrial-grade VFAs has been reported to be 4–25 times the price of CH_4 generated by anaerobic digestion (AD) [68, 70]. This growing demand has been attributed to rising costs of key petroleum-based precursor materials, as well as energy and transport costs [68].

VFAs can be further transformed into polyhydroxyalkanoates (PHAs), which are biopolymers produced by bacteria as carbon and energy reserve molecules [71]. PHAs have properties comparable to polyolefins, making them suitable as biofuels, precursors for chemical synthesis, or as biodegradable plastics [70, 72]. Current industrial-scale PHA production uses pure culture systems and expensive carbon sources, making PHA market prices 2-5 times more expensive than petroleum-based plastics [73, 74]. Nevertheless, the global market is expected to grow from US$62 million to US$121 million by 2025 (CAGR = 14.2%) due to increasing demand from the packaging, food and beverage, biomedical, and agricultural sectors [75]. Recent studies have shown promising PHA yields from sludge fermentation [73, 76], with one study suggesting a fivefold increase in product revenue if wastewater processes were optimized for PHA production compared with AD [71].

Lastly, there exist complementary technologies for enhancing AD, as well as competitive processes for resource recovery. Depending on treatment intensity, different valuable end-products may be obtained. The next section will present these technologies in detail.

4.1 Technologies for VFAs and PHAs recovery

The general process flow for VFA production includes pre-treatment of the biological feedstock to enhance biodegradability by breaking down lignin and cellulose and partially hydrolyze the carbohydrates. These can be achieved by mechanical, chemical (acid/alkaline), thermal, thermochemical, and biological (e.g., enzymes) means [71], with chemical treatments being the most mature. However, these techniques have not been optimized for VFA production, but rather for AD pre-treatment. Since different feedstocks pose different challenges to solubilization, different pre-treatments should be considered on a case-by-case basis [77]. Thereafter, the treated feed undergoes acidogenic fermentation to produce a VFA-rich broth, with other by-products such as hydrogen (H_2), carbon dioxide (CO_2), alcohols, and other organic acids. This process has been alternately termed as the carboxylate platform [78], and critical parameters include the organic loading rate (OLR), hydraulic retention time (HRT), temperature, and operating pH [71, 77]. Finally, the VFA products can be recovered from the mixed VFA broth, with membrane extraction, electrodialysis, and filtration being the most studied methods [77]. Overall, technological developments have centered around using different feedstocks and estimating general VFA yield without regard to specific end-products in mind [77]. The lack of process optimization and integration, coupled with the scales of recent studies [79, 80], positions VFA recovery at a Technology Readiness Level (TRL) of 4–5. Commercial research consortiums (e.g., CAFIPLA in Europe) have also been actively engaging in process scale-up for VFA recovery from heterogeneous wastes (e.g., municipal organic waste/sewage sludge) as feedstocks [81].

Instead of VFA concentration and valorization from the broth, an additional bioconversion to PHAs can be achieved by splitting the broth stream into two: one to a mixed microbial culture for selection of PHA producing bacteria, and the other is mixed aerobically with the enriched culture for PHA bioaccumulation [74, 76]. The key operational parameters that influence the quality and composition of PHA include the feedstock origin and composition, aeration, temperature, pH, culture characteristics, and solids retention time (SRT), among other factors [76, 82, 83]. Thereafter, the bacteria containing the PHA is settled and sent for chemical treatment (consisting of a combination of acid, alkali, hypochlorite, and surfactants) to harvest the intracellular PHA [76, 84]. Compared to enzymatic and chemical synthesis (polymerization) of PHA, microbiological production has been held up as the “gold standard” due to cost-effective production without the use of expensive co-reagents [83]. PHA production using feedstocks such as activated sludge (AS) [85, 86] and AS mixed with the organic fraction of municipal solid waste [74] have been demonstrated up to the pilot level. Other authors have also conducted process design, techno-economic, and environmental impact studies for PHA production [74, 84], with another investigating the feasibility of wastewater treatment plant retrofit into PHA bioresource factories [73]. The company Oerlemans Plastics has also announced their intention to scale their PHA process up from their pilot trials [87]. The estimated TRL for PHA production from sewage sludge is 4–5.

4.2 Biomass recovery

Anaerobic digestion (AD) is considered as the resource recovery standard for the conversion of organic carbon, biomass, into a useful end product (biogas or methane (CH_4). Complementary technologies to enhance CH_4 and energy yield may be generally classified as AD pre-treatment and post-treatment respectively. Thermal pre-treatment is a well-developed process: heating the sludge to disrupt the biomass cell walls solubilizes its contents and results in higher CH_4 yields and reduces the volatile solids (VS) content of the sludge [88]. Companies like Cambi (Norway) have developed thermal hydrolysis as a commercial solution (TRL 9) [89]. Their 30-minute treatment at 180°C was reported to increase CH_4 production by 150% while reducing VS by 30% [88]. Cambi currently has operational facilities in Singapore with plans for expansion [90]. Another mature technology (TRL 9) is the wet-air oxidation (WAO) process that subjects the biomass to high temperatures (150–320°C) and pressures (20–50 bar) for 15–120 minutes to be oxidized. The benefit of WAO is that harmful by-products associated with incineration (gaseous and carcinogenic pollutants, as well as fly ash) are not generated, and the organics are converted into harmless products [91]. WAO may also be used for VFA production from biomass [92]. However, relatively few plants at scale are in operation due to cost and operational issues [91], but Siemens and Veolia still offer solutions as of the time of writing [93, 94]. Other noteworthy pre-treatment technologies include ultrasound disruption by induced cavitation and advanced oxidation processes (AOPs). Ultrasound (TRL 9) has been reported to reduce sludge viscosity and slight increases of CH_4 yield in downstream AD [95], with Ultrawaves as one of the main suppliers [96]. Ozone and other proprietary AOPs are also commercially available (TRL 9) for sludge pre-treatment, and can release nutrient-rich by-products (nitrogen and phosphorus) along with the solubilized sludge [97-99]. Minor methods for breaking down cell walls include mechanical treatment by pressure homogenization (compressing the sludge to 60 MPa) [100] and by chemical treatment with acid/alkali. These last two methods have seen limited use due to their low efficiencies [88].

AD post-treatment after dewatering may include sludge drying as well as incineration, conventional thermal technologies (TRL 9) that minimize the sludge disposed. Incineration technology is well established in Singapore and is used to combust both municipal solid waste and digested sludge, with the benefit of modest energy recovery [2, 101]. Fluidized bed incineration, which operates at 800–1150°C with fluidized sand to facilitate the breaking up of sludge into particles, is featured in Singaporean installations and companies [102, 103]. WAO can also be applied to digested sludge [94].

Competitive technologies that can replace AD as the main resource recovery stage include thermochemical and hydrothermal treatments. Technologies in the former category include pyrolysis, which operates at 300–900°C in the absence of air to produce pyrolytic oil, biochar, and non-condensable gases (CO, H_2, CO_2, CH_4, and light hydrocarbons), while gasification facilitates partial oxidation at 650–1000°C to maximize syngas production. All products formed can be upgraded as fuels or as chemical feedstocks, or be combusted for energy recovery [104]. Commercial pyrolysis solutions (TRL 8–9) are offered by AquaGreen (Denmark) for sludge treatment [105] and Environmental Solutions (Asia) (Singapore) for the conversion of plastics to fuel [106]. While the latter company does accept sludge from customers, there is no indication that pyrolysis has been applied for sludge treatment. The hydrothermal treatment represents an emerging class of technologies operating at high temperatures and pressure in a sealed vessel, whereby water is the main reactant. These processes may be classified as hydrothermal carbonisation (HTC), hydrothermal liquefaction (HTL) and supercritical water gasification (SCWG), according to the temperature, pressure and residence time of the process. Accordingly, different products analogous to the thermochemical products may be obtained. HTC mainly produces a solid phase known as hydrochar. HTL yields both hydrochar and bio-oil, and SCWG generates H_2 and CH_4 [107, 108]. The key advantage of these processes compared with thermochemical treatment is the negation of energy required for sludge drying before treatment [107]. It could be applied upstream for AD pre- or post-treatment as well. However, hydrothermal processing remains far from commercialization (TRL 2–4).

Table 6 summarizes the technologies available for the recovery of VFAs, PHAs, and other resources from biomass, and what are the expected products formed. Commercial entities involved in these technologies' development with their TRLs are also presented.

Table 6 Summary highlights of VFAs, PHAs, and biomass recovery technologies, products obtained, and overall TRL

	Technologies (Relevant company, Country)	Products formed: Major, *Minor*	Overall TRL
VFAs	Carboxylate platform (CAFIPLA Consortium, Belgium; NUS, Singapore)	**Acetic, propionic, butyric acids,** H_2, CO_2, alcohols, other organic acids	4–5
PHAs	Selection of PHA-producing bacteria and harvesting (RWDC industries, USA; Oerlemans Plastics, Netherlands)	Mixed PHAs	4–5
Biomass	Anaerobic Digestion (AD) Pre-treatment		
	Thermal hydrolysis (Cambi, Norway)	**Treated Sludge for AD**	9
	Wet-air oxidation (Siemens, Germany; Veolia, France)	**Treated Sludge for AD, VFAs**, water, minerals	9
	Ultrasound (Ultrawaves, Germany)	**Treated Sludge for AD**	9
	Ozone (Air Liquide, UK; Praxair, India)	**Treated Sludge for AD, nutrient-rich liquids, phosphorus**	9
	Main sludge treatment processes		
	AD (Veolia, France)	**Biogas**, **heat**, water, digestate	9
	Pyrolysis, gasification (AquaGreen ApS, Denmark)	**Solid**: biochar **Liquid**: Oils, water, tar, organics Gas: H_2, CH_4, CO_2	7–9
	Hydrothermal carbonisation Hydrothermal liquefaction Supercritical water gasification (SunCoal, Germany; TerraNova, Germany; Ingelia, Spain)	Hydrochar, nutrient-rich liquids, bio-oil, H_2, CH_4	2–4
	Dewatered digestate treatment		
	Sludge drying (Veolia, France; Eco, Singapore)	Dried sludge, water	9
	Fluidized bed incineration (Yamato Sanko, Japan; Novexx, Singapore)	Energy, bottom ash, water	9

5 Drivers and constraints for resource recovery in Singapore

The National Environment Agency (NEA) and the Public Utilities Board (PUB), which is Singapore's national water agency, are the statutory boards under the Ministry of Sustainability and Environment (MSE)[1], that collectively manage Singapore's lived environment and water resources, respectively. Currently, the recovery of resources, such as phosphate and cellulose, from wastewaters is not fully addressed neither within Singapore's wastewater management framework nor the legal framework for the water sector, which is set by the 'Public Utilities Act', the 'Public Utilities (Water Supply)' and the 'Sewerage and Drainage Act' [109]. There are neither policies in place for the recovery of compounds from reclamation plants, regulations for ensuring the quality of recovered products, nor economic incentives to recover valuable components.

Regulations in Singapore are mainly focused on water environment protection, e.g., mitigating eutrophication, and therefore are aimed to establish allowable limits for effluent discharge to a watercourse or controlled watercourse for compounds such as phosphate, which limit the concentration of trade effluent discharge to watercourse and controlled watercourse are 5 ppm and 2 ppm, respectively.

PUB's strategy, when it comes to closing the water cycle, is towards integrated management of both water and wastewater to supply high-quality water while recovering energy, mainly via anaerobic digestion and incineration of digested sludge [110, 111]. PUB is actively looking at technologies that have the potential to significantly reduce energy consumption and chemical usage in liquid stream treatment, and processes that produce more biogas and generate less sludge in solids treatment. To further reduce the sludge footprint, pre-treatment methods to improve the rate of sludge destruction in digesters are also being explored. Phosphate recovery is listed as a long-term goal that Singapore wants to achieve alongside the recovery of other resources from wastewater and sludge. Ultimately, PUB aims to achieve energy self-sufficient water reclamation plants to ensure long-term sustainability [5]. In this regard, PUB and NEA are building a facility, i.e., The Tuas Nexus, that integrates wastewater, domestic and industrial, and solid waste treatment in one place [54]. According to NEA, this integration will help to maximize energy and resource recovery. However, the emphasis on resource recovery is placed on the energy that will be obtained from the co-digestion process of food waste and wastewater sludge.

The Tuas Nexus facility is a great initiative with a lot of potential for resource recovery other than water and energy. It is expected that about 70% of Singapore's water demand will come from the non-domestic sector by 2060 [111], which will open opportunities for the development and adoption of solutions that target the recovery of valuable resources from industrial wastewaters [5].

Overall, increasing resource recovery in Singapore requires identifying a market, end-users, for the recovered products. The PUB together with NEA should partner with other stakeholders, e.g., universities and companies, to i) conduct a process design and techno-economic analysis that can give insights to justify a transition towards the recovery of specific compounds, and ii) identify interactions of the recovery processes and the products with the environment and the stakeholders, e.g., the public perception of the recovered compounds. In general, there is a knowledge gap in establishing a more comprehensive framework for planning, decision-making, and assessment of resource recovery.

In the case of phosphate recovery, it is important to take into account that in the past decades there has been a decline in the use of fertilizers in Singapore. Currently, agriculture only represents less than 1% of the economic activity [11]. Nevertheless, the Singapore Food Agency (SFA) encourages to grow local to provide buffer supply to enhance food security and sets the goal to achieve 30% local

[1] The ministry was formerly named as the Ministry of Environment and Water Resources (MEWR).

production by 2030 [112]. This may increase the market demand for fertilizers in the future and pose as a driver for phosphate recovery. Additionally, recovered phosphate can be labeled as sustainable, which can find a niche market in small amateur farmers locally and abroad. An important aspect to consider is the form of the recovered phosphate, e.g., struvite. The market value of struvite is hard to estimate due to a lack of knowledge and trust of farmers in its fertilizing potential. The recovered struvite is still more expensive than phosphate rock, and it represents a small percentage of global phosphate supplies, which has hindered current interest from the fertilizer industry. This weak market competitiveness is likely to result in the lack of market demand for recovered phosphate products [42, 113, 114].

The potential recovery of cellulose is linked to finding new niche markets (home and abroad), applications, and partners are supposed to be identified with unique selling propositions to increase competitiveness and make the resource recovery route successful [9, 42, 61]. Potential applications for recovered cellulose include soil conditioner, fuel for biomass combustion plants, feedstock for the fermentation industry, aggregate for construction materials (e.g., asphalt), and raw material for the paper pulp industry. Another interesting emerging application of cellulose is its refinement into nano-cellulose – a nanocomposite with unique properties. The production of new toilet paper is also possible [42]. The wide application opportunities imply a big market that could be a driver for cellulose recovery.

When it comes to the recovery of VFAs, and PHAs, Singapore faces similar challenges and developmental bottlenecks as other countries that aim to recover these compounds. There is a relative lack of data on the process costs for separation and purification of VFA from the mixed broth and PHA from the settled culture, respectively [71, 77, 84]. These costs can be important determinants for whether the overall resource recovery operation can be feasible in the first place. In addition, Singapore’s strategy, as we mentioned previously, is focused on maximizing energy recovery through the anaerobic digestion of sludge. Therefore, any replacement process will compete will existing sludge treatment processes and will require restructuring of reclamation plants infrastructure.

In Table 7 and 8, we have summarized key drives and constraints for resource recovery from wastewater in Singapore.

Table 7 Drivers and constraints for phosphate and cellulose recovery in Singapore

Compound	Drivers	Constraints
Phosphate	• Sustainability development goals (SDGs) • Circular economy • Energy conservation • The international trend towards resource recovery • Food security: "30 By 30" Local Production Goal • Potential demand for sustainable fertilizers locally and abroad	• Low local food production • Competition with conventional fertilizers that might have lower prices • Low awareness among farmers about using fertilizers from recovered phosphate • Integrated approach in reclamation plants is missing •
Cellulose	• Implementation opportunities in niche markets, e.g., aggregate for construction materials • Technological feasibility: TRL=7 (SMART-Plant, 2017) ■ Reuse for paper: TRL=5 (Zijp et al., 2017) ■ Reuse for construction and for bioenergy (e.g., biogas): TRL=7 (Zijp et al., 2017; Cirtec B.V., 2020)	• Cellulose is not a stand-alone product • Investment costs • Uncertain return on investments • Lack of public-private partnerships to market products • Social acceptance of certain products, e.g., cradle-to-cradle toilet paper

Table 8 Drivers and constraints for VFAs and PHAs recovery in Singapore

Compound	Drivers	Constraints
VFAs & PHAs	• Possible increase of sludge generation in the TWRP. • End-user for PHA already existing. There is a Singaporean company (RWDC Industries) that manufactures biodegradable single-use plastic substitutes [115].	• Competition with the use of wastewater sludge to produce biogas • Technological challenges to ensure consistent and pure VFAs. • Technological challenges for PHAs extraction and purification. • Lack of data on operational costs for separation and purification of the product.

6 Resource recovery from domestic wastewater in the Netherlands

In the Netherlands, the water sector, consisting of drinking water companies, municipalities, and waterboards, cooperate and discuss strategies to achieve circularity and minimize waste. The waterboards, which are the authorities in charge of wastewater treatment, manage about 350 WWTPs [116]. Their ambition is to turn these treatment facilities into ‘factories’ where clean water is produced, and energy and all possible raw materials contained in the wastewater are recovered and reused [117].

When it comes to resource recovery from domestic wastewater in the Netherlands, these are some of the relevant aspects to point out:

- Phosphate is recovered, mainly as struvite, at ten of the treatment plants [118]. One of the largest installations for phosphate recovery is managed by Waternet, the water utility of Amsterdam, which recovers about 1000 tonnes of struvite per year [9]. Another three WWTPs have carried out pilot-scale tests to recover phosphate as vivianite.
  Two sewage sludge processor companies, HVC and SNB, are conducting feasibility tests to recover this phosphate from combustion sludge ash [119]. The process is expected to recover about 80% of phosphate in the form of phosphoric acid.

- Cellulose is removed from the sewage water, but so far the material has not been reused on a large scale. Cellulose is harvested in five WWTPs, and seven other plants have conducted studies on the filtering, harvesting, and purification process. These studies have shown that filtering sewage water for the extraction of cellulose is not yet profitable, mainly due to the low cellulose yield obtained [120].

- The Netherlands is a frontrunner in the recovery of biodegradable materials from wastewater: bioplastics and biopolymers. The potential for the production of biopolymers in the form of PHAs and PHBV (Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)) has been explored in several pilot trials. Currently, five waterboards are taking steps towards the construction of a large-scale demonstration plant for the production of PHBV. The technology to recover the bioplastics is been developed by Paques [121] in collaboration with Delft University of Technology (TU Delft). The plant is expected to be operational at the end of 2021.
  A novel process for the extraction of biopolymers has been developed by Royal HaskoningDHV also in collaboration with TU Delft. Kaumera Nereda® Gum is the biopolymer extracted from the aerobic granular sludge from the Nereda wastewater treatment process [122, 123]. Potential applications of this biopolymer reside in its versatile properties as both water adsorber and repellent, and also fire-retardant [124]. Kaumera Nereda® Gum is produced in two plants in the Netherlands: one plant with the capacity to produce 400 tonnes of biopolymers per year and the other one 50 tonnes/year [124].

- Twelve WWTPs have been transpformed into ‘Energy factories’, and preparations are underway to transform another eleven plants [125].

- One development based on the concept of WWTPs as factories is the ‘Water Factory Wilp’. This factory will treat sewage water of about 17 thousand households, and in the process cellulose, phosphate, ammonium, and other organics will be recovered [126]. The treatment process will consist of a combination of physicochemical treatment technologies (such as nanofiltration, dissolved air flotation (DAF), and ion exchange) and a natural filtration system consisting of wetlands and reeds, Figure 5. The factory is the result of the close collaboration between the waterboards and the research institute STOWA, and companies—Witteveen+Bos, Royal HaskoningDHV, Attero, Aquaminerals. It is expected that the Water factory will be fully operational in 2024.

Figure 5 Schematic diagram of unit processes in the sewage water treatment at the Water Factory Wilp. 1-2) Screens and sand trap units; 3) fine sieve installation to remove cellulose; 4) electrocoagulation unit that promotes the coagulation and flocculation of phosphate and organic material; 5) dissolved air flotation (DAF) unit; 6) nanofiltration unit; 7) ion-exchange process for ammonium removal; 8) helophyte filter; 9) clean water is released (Figure taken from [126])

7 Concluding remarks

Singapore's strategy towards resource recovery is mainly focused on water reuse and energy recovery by increasing biogas production from anaerobically digested sludge. However, Singapore's vision and commitment to sustainable development are good drivers that might lead the country to explore other strategies to increase resource recovery from different waste sources, including wastewater.

In the path to increasing resource recovery, Singapore first needs to address how to combine the available technologies with current infrastructure to maximize the productivity of the reclamation plants. It is important the involvement of different parties, e.g., public organizations, knowledge institutions, companies, and individuals, to i) identify the most suitable approach for resource recovery, and ii) evaluate the impact of these approaches, e.g., whether the use of recovered resources or the recovery process will entail risks to human health or cause environmental problems.

For most of the compounds that can be recovered from wastewater, there are still uncertainties on the market value and end-users, which can make reclamation plants hesitant about venturing to recover certain compounds that could affect their operations costs. However, if utilities are to be seen as resource factories, then planning is needed to transition towards resource recovery with an eye on the market potential and quality of the products to be offered to the local/international economy.

Abbreviations

ACP	Amorphous calcium phosphate
AD	Anaerobic digestion
AOP	Advanced oxidation process
CADoS	Cellulose Assisted Dewatering of Sludge
CAPEX	Capital Expenditure
COD	Chemical Oxygen Demand
CSH	Calcium Silicate Hydrate
CSTR	Continuous Stirred Tank Reactor
DCP	Dicalcium Phosphate
EBPR	Enhanced Biological Phosphorus Removal
ESPP	European Sustainable Phosphorus Platform
EU	European Union
FO	Forward Osmosis
HAIX	Hybrid Ion Exchange Media
IEX	Ion Exchange
IWMF	Integrated Waste Management Facility
MAP	Struvite/mineral substance composed with magnesium ammonium phosphate
MBR	Membrane Bioreactor
MCP	Monocalcium Phosphate
MF	Microfiltration
Min (EWR)	Ministry of the Environment and Water Resources
NEA	National Environmental Agency
NGO	Non-governmental organization
NP	Nitrogen-phosphate
NPK	Nitrogen-phosphate-potassium
NTU	Nanyang Technological University, Singapore
NTU FST	Nanyang Technological University Food Science and Technology
NUS	National University of Singapore
NWP	Dutch Nutrient Platform
OMBR	Osmotic Membrane Bioreactor
OPEX	Operating Expenditure
P	Phosphorus
PK	Phosphate-potassium
PUB	Public Utilities Board
SDGs	Sustainability Development Goals
SFA	Singapore Food Agency
SSA	Sewage Sludge Ash
TP	Total Phosphorus
TRL	Technology Readiness Level
TSS	Total Suspended Solids
TWRP	Tuas Water Reclamation Plant
UN	United Nation
UPWRP	Ulu Pandan Water Reclamation Plant
VS	Volatile solids
WAS	Waste Activated Sludge
WAO	Wet-air oxidation
WASSTRIP	Waste Activated Sludge Stripping to Remove Internal Phosphorus
WWTP	Wastewater Treatment Plant

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ANNEX 1. Students' reflection

In this part, we include the thoughts and considerations of the students that carried out the desk study.

a. Jonathan Zhiqiang Lee

Discussions with our Dutch counterparts produced a deeper appreciation for their operating and regulatory context. Given that the Dutch local water boards have far more autonomy in managing their operations, their technology application and operating experience for resource recovery are comparatively more advanced and extensive. This is especially so for phosphorus recovery, as it is recycled into the agricultural sector – a major part of the Dutch economy. This expertise could also become an economic advantage as the Netherlands is pushing for 100% phosphorus recovery from wastewater for export. Cellulose recovery is also incentivized by virtue of commercial demand, with Europe being the second-largest cellulose fiber market in the world. One similar facet of Singapore and the Netherlands is the deep collaboration between different stakeholders to advance technological development towards the realization of a CE. This project has shed invaluable light on the different drivers and planning needed to realise circular practices in the unique local and regional economies of both countries.

b. Roujia Qiu

Singapore and the Netherlands do have similarities in resource recovery. For example, some of the drivers and barriers for phosphate and cellulose recoveries are identical for both countries. However, there are differences in the contexts and applied technologies in the Netherlands and Singapore.

Firstly, the recovery technologies applicable in Singapore and the Netherlands are different. Singapore emphasizes water reuse due to the shortage of natural freshwater supply. Back in 2003, Singapore has launched a project called "NEWater" to achieve the goal of "toilet to tap". In Singapore, the research on phosphate recovery is currently at the lab scale and there is no direct research on cellulose recovery from domestic wastewater. In addition, the low phosphorus concentration in domestic wastewater and the little demand for fertilizers may also impede the application of phosphate recovery in Singapore. On the opposite, the Netherlands has equipped many WWTPs with phosphate recovery technologies for many years. The phosphate recovery technologies available in the Netherlands include precipitation, crystallization, and thermal treatment processes (i.e., ANPHOS®, PHOSPAQ®, PhoStrip, Airprex®, NuReSys®, Crystalactor®, and Thermphos®). In recent years, the Netherlands has also developed fine-screen technologies for sieving cellulose from wastewater and installed pilot-scale cellulose harvesting systems in some WWTPs.

Secondly, Singapore's context differs from the Netherlands's context. Currently, there is no specific legislation or policies related to phosphate and cellulose recoveries in Singapore. However, there are various policy documents on resource recoveries in the Netherlands. For instance, in 2015, the "fertilization law" in the Netherlands incorporated into an article for recovered phosphate; in 2017, the *Ambitie Nutriënten 2018* was proposed to promote the further deployment of phosphate recovery in the Netherlands; and the target set by the raw materials and energy factory in the Netherlands is to recover 25% of all the cellulose from the Dutch sewage water in 10 years.

Thirdly, Singapore could be at its infancy stage in coordinating different stakeholders on the resource recovery, but there is a lot of interaction among the stakeholders about resource recovery in the Netherlands. The Dutch Nutrient Platform (NWP) on the national level serves as a hub for information exchange, and it promotes communication among all cross-sectoral stakeholders. This Dutch platform, along with the European Sustainable Phosphorus Platform (ESPP), has driven the development of several soft legislative tools and research initiatives within the national sector appealing for a collaborative research environment across various stakeholder groups involved in P management in Europe. One successful example is that ESPP facilitated "The Dutch Phosphate Value Chain Agreement" in 2011 which called for a commitment to the establishment of a sustainable

Sustainable development requires disruptive changes in the way of our societies and business organizations. In the linear economy, raw natural resources are taken, transformed into products, and finally get disposed of as waste. On the opposite, the circular economy aims to narrow the gap in the production and the natural ecosystems' cycles which humans ultimately depend upon. The circular economy approach provides ideas and methods for innovation and integration between natural ecosystems, our daily lives, businesses, and waste management.

Although the original goal of wastewater treatment is to remove contaminants and pathogens to recover water and protect water quality, today scarcity of resources and sustainability are driving major global changes. Shifting away from WWTPs to water resource recovery facilities becomes significant for the value realization of wastewater in the context of circular economy. It will become a general trend to improve sustainability by recovering valuable components from wastewater and utilizing them for beneficial purposes.

In this report, we aim to integrate useful knowledge associated with resource recovery from domestic wastewater. Although their recoveries have been implemented in several countries for years and decades, especially the phosphate recovery, we still need to recognize Singapore's context and pinpoint how phosphate, cellulose, and other compounds recovery from domestic wastewater are relevant to us. It is important to incorporate resource recovery and circular economy principles in our strategy and investment planning as well as infrastructure design.

By learning from the Netherlands and other countries, numerous technologies have been developed for recovering phosphate from domestic wastewater which varies significantly with their operational scale, costs, performance, etc. Cellulose recovery is still an emerging topic, and only a few countries are researching cellulose recovery from domestic wastewater. Selection of the most appropriate technologies of phosphate and cellulose recoveries for implementation should include an up-to-date review of technologies to identify their feasibility in our context. Recovery efficiencies, economic performances, and environmental impacts are also important considerations. Besides, developments in international strategies and policies related to phosphate and cellulose recoveries should be monitored in terms of their implications for implementing their recoveries.

The low phosphorus concentration in domestic wastewater would be the biggest barrier for phosphate recovery in Singapore, as the struvite precipitation (one of the most economic phosphate recovery processes) usually requires at least 50 mg/L P in the liquid phase. Therefore, it is more appropriate to use the phosphate-rich side stream or supernatant from digested sludge to remove and recover the phosphate simultaneously in the WWTPs with EBPR. According to some studies in Singapore, urine could also be used as a source for struvite recovery, but many practical issues (e.g., urine separation, urine storage, social acceptance, etc.) need to be addressed.

Besides, ion exchange or reversible adsorption with high phosphate selectivity could also be an attemptable process for Singapore to recover phosphate from phosphate-rich side stream, supernatant from digested sludge, or secondary treated effluents (without phosphate removal step during wastewater treatment). When developing this process, the adsorption/ion exchange capacity and recovery efficiency should be tested under different conditions (e.g., the particle size range of adsorbent/ion exchange media, pH, and temperature).

Cellulose recovery is theoretically possible in Singapore. By installing a rotating belt filter in the primary treatment stage of WWTPs, cellulose can easily be collected. Nevertheless, this technology could increase the maintenance costs, as the fine mesh (≤0.35 mm) requires regular cleaning, inspection, and maintenance to prevent and/or remove the screen plugging by the influent solids. It is expected to pay attention to this problem and find a solution during the trial and error phase.

In summary, resource recovery is not a simple and short-term process, and it is necessary to establish a comprehensive framework for Singapore to implement resource recovery in the context of circular economy and sustainable development in the future. Long-term national strategies in relation to wastewater treatment and sludge management should consider the potential phosphate/cellulose recovery. Identification of available outlets for the recovered phosphate and cellulose should be undertaken as part of selecting phosphate and cellulose recovery technologies. The establishment and implementation of phosphate and cellulose recoveries should involve close coordination between relevant stakeholders (e.g., WWTPs, policymakers, NGOs, researchers, etc.).

c. Laetitia Ingabire

In the Netherlands, the domestic wastewater treatment technologies for valuable components recovery are on different scales. Some technologies are commercially applicable. For example, excess phosphate and cellulose recovered in the Netherlands are exported to other countries. Other technologies are technically feasible but not economically viable. However, other technologies are under development (laboratory scale). There is a strong collaboration between government, research institutions, and academic institutions that helps in developing sustainable technologies. Moreover, Netherlands can adopt other treatment technologies from other countries for optimal and beneficial resource recovery as it is the Netherlands' plan of most sustainable technology application.

Furthermore, the transition from governmental resources recovery based to business resources recovery based will help optimize resource recovery and bring the financial interest to companies. Therefore, there are many things Singapore and other countries can learn and adopt from the Netherlands. Firstly, Singapore can adopt recovery of resources like PHAs, cellulose, and others from domestic wastewater. Secondary, the resource recovery purpose for Singapore could not be only for effluent concentration reduction from WWTPs but also for recycling purposes. Thirdly, the challenges of excess resources recovered in Singapore can be solved by exporting those resources to other countries with scarcity. Moreover, the circular economy for sustainable resource management is achieved too. Therefore, the strong collaboration of different sectors like universities, research institutions, and government to assess the sustainable feasibility of treatment technologies is required.

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