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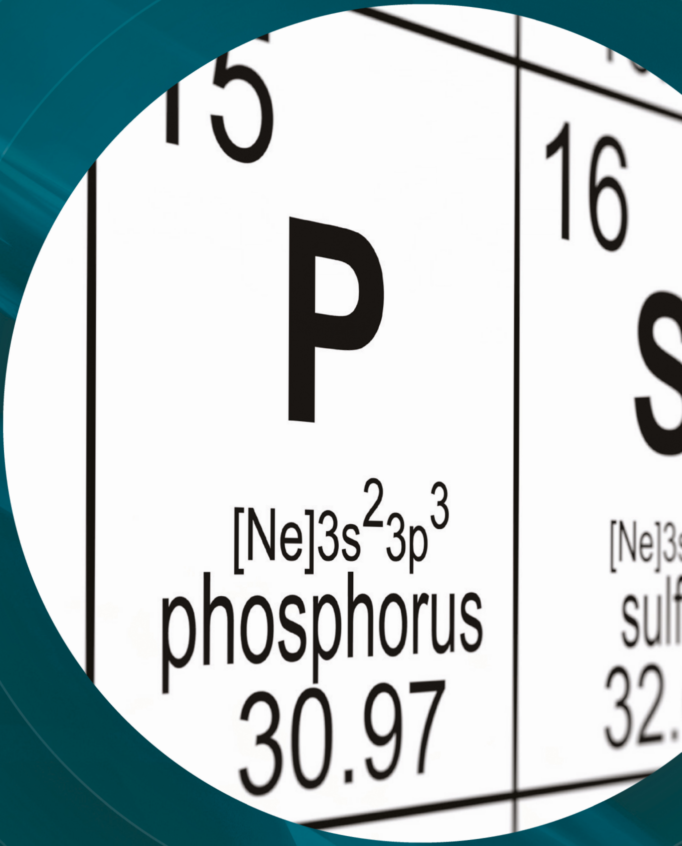

Phosphorus: Polluter and Resource of the Future

Removal and Recovery from Wastewater

Editor: Christian Schaum

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Chapter 19

The Pearl® and WASSTRIP® processes (Canada)

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19.1 INTRODUCTION

The Pearl® process is the core of Ostara's nutrient recovery solution. The Pearl process is operating at 14 municipal wastewater treatment plants (WWTPs) in North America and Europe, where it extracts phosphorus and ammonia from nutrient-rich flows, converting these nutrients into high-purity struvite pellets. Ostara manages this recovered material, and sells it as premium quality, slow release fertilizer, branded Crystal Green®. We commit to purchase every tonne of Crystal Green produced by the WWTP for a guaranteed price.

The waste activated sludge stripping to recover internal phosphorus (WASSTRIP®) process complements the Pearl process by releasing phosphate, magnesium, and potassium from waste activated sludge (WAS) prior to thickening. Thickening separates these soluble components from the solids, preventing them from entering the digester, where they can adversely impact performance. Thickening liquor

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is treated in the Pearl process with digested sludge dewatering liquors, avoiding nutrient return to the plant and increasing Crystal Green production.

19.2 THE PROCESS

19.2.1 The Pearl process description

The Pearl process recovers phosphorus from nutrient rich wastewater liquors, through the controlled precipitation of struvite. Primary system feed streams include post-anaerobic digestion sludge dewatering liquors, and WAS thickening liquors after phosphate release using the WASSTRIP process. The process has also been successfully applied to mainstream wastewater treatment when nutrient concentrations are high.

The Pearl reactor is an expanding up-flow fluidized-bed reactor. Two principles are fundamental in the process – maximizing efficient nutrient removal and consistently recovering high quality, commercial fertilizer. The Pearl process design incorporates features that support these objectives, such as reactor geometry and process control methodology.

The Pearl process is controlled through chemical addition: soluble magnesium salts are added to affect ionic concentration and, if required, sodium hydroxide is added to adjust pH. The chemicals and side-stream influent are then introduced into the bottom of the reactor, where struvite crystallization begins to occur.

Treated effluent is discharged from the top of the reactor and returned to the WWTP for further treatment. A portion of treated effluent from the top of the reactor is returned to the bottom of the reactor in a recycle loop. This allows for

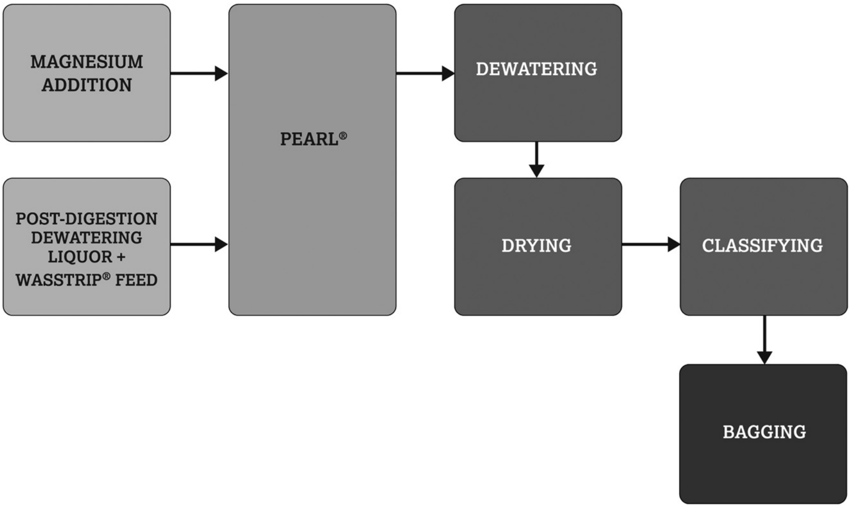

Figure 19.1 Process scheme.

control of product size, as well as adaption of the system to variable feed flow rates. Recycle rates are automatically controlled by the Pearl Control System, and do not impact overall phosphorus removal efficiency.

Growing fertilizer pellets in the reactor are held in suspension using the recycle stream. The inventory of fertilizer in the reactor is measured using instrumentation. When a target fertilizer inventory in the reactor is reached, the reactor will automatically harvest the fertilizer by sending it to the product handling system. The product is dewatered, heat dried, sorted by size, and optionally stored in silos in a simple and fully automated process. Periodically the silo contents are bagged in one tonne flexible intermediate bulk containers (IBCs) and stored until sale. During harvest, the reactor will continue to be fed side-stream nutrients and perform nutrient removal without interruption or loss of efficiency.

The entire system process flow is shown schematically in Figure 19.1.

19.2.2 The WASSTRIP process description

The waste activated sludge stripping to recover internal phosphate (WASSTRIP) process releases phosphate from WAS. The WASSTRIP process consists of a mixed tank maintained in an anaerobic condition. Phosphate accumulating organisms (PAOs) in enhanced biological phosphorus removal (EBPR) sludge readily release stored phosphate (together with magnesium and potassium counter ions) in WASSTRIP's anaerobic conditions. Subsequent sludge thickening diverts released nutrients into thickening liquor, which the Pearl process recovers. Due to the fact that the WASSTRIP liquor is low in ammonia, the stream needs to be combined with dewatering liquors in Pearl in order to precipitate struvite.

WASSTRIP controls struvite precipitation throughout the sludge treatment stream by reducing the phosphate and magnesium content of the WAS before anaerobic digestion (where ammonia forms). This improves sludge treatment performance, tackles struvite related maintenance, and significantly reduces sludge production. WASSTRIP also reverses the negative impact of EBPR on dewaterability.

The WASSTRIP process hydraulic retention time (HRT) is influenced by WAS phosphorus content and volatile fatty acid (VFA) availability. PAOs cannot release phosphate unless sufficient VFAs are present to be absorbed. VFAs are created as WAS ferments. WASSTRIP can operate endogenously on WAS only, or VFAs can be added to the WASSTRIP process (e.g. from primary sludge fermentate, acid phase digestate, etc.) to accelerate phosphate release and reduce HRT.

19.2.3 Crystal Green

The Pearl process produces struvite in a market-ready fertilizer granule branded as Crystal Green. The production of a granule of specific size (>0.5 mm in diameter) allows it to be easily separated from wastewater biosolids, resulting in a product that is completely free of organic matter.

As a high-value fertilizer, Crystal Green is registered in Canada, 44 US states, Taiwan and Puerto Rico. It complies with European fertilizer Regulation (EC) No 2003/2003 and meets required limits for organic and inorganic constituents. Ostara's precise crystallization and heat treatment process ensures only nutrients are extracted, resulting in an end product that is 99.6% pure with no pathogens, and lower salts and heavy metals than any other phosphate fertilizer available on the market. The sizes harvested in the Pearl reactor are specific to meet market demands in turf and agriculture, ensuring market demand. All Crystal Green produced by Ostara's facilities meets regulatory and market requirements.

Crystal Green has attributes that are superior to commercially available inorganic fertilizers. Crystal Green is not water soluble – it is root activated. When a plant needs nutrients, its roots excrete organic acids that dissolve nutrients from the soil. When a plant excretes organic acids, Crystal Green releases nutrients so the plant can absorb them. Traditional phosphorus fertilizers are water soluble. When it rains or the soil is irrigated, the nutrients dissolve into the water. When the plants cannot use all the dissolved nutrients, they are washed away with the water, ending up in the water environment or leaching into the soil beyond the root zone or the phosphorus may bind with other constituents in the soil that render it unavailable to plants. Crystal Green not only eliminates diffuse phosphorus pollution; it provides a much more efficient nutrient delivery mechanism to the plant. This sets up a positive feedback loop where less phosphorus is applied, more gets to the plant, and less gets into the water environment.

Concurrently with the construction of an Ostara facility, Ostara enters into a long-term fertilizer offtake agreement with the facility owner. Under the terms of this agreement, Ostara agrees to buy the fertilizer produced by the facility and the owner agrees to sell the fertilizer to Ostara. The agreement sets out a pre-agreed price for the fertilizer (either fixed throughout the term or indexed to commodity fertilizer prices, depending on customer preferences). While the customer takes responsibility for operating the facility, Ostara continues to provide high-level production support to the owner through the life of the offtake agreement. This arrangement ensures a steady, reliable stream of revenue to the facility owner and relieves the owner of the risks and challenges surrounding the marketing and distribution of the fertilizer. At the same time, the agreement guarantees a steady supply of fertilizer to Ostara. By taking advantage of the scale afforded by aggregating the supply from multiple facilities, Ostara is able to access markets which would be inaccessible to any individual facility operating on its own behalf.

19.2.4 Key figures of the process

The Pearl reactor is available in standard models sized by PO4-P mass loading. Current models are available ranging from 65 to 1260 kg PO4-P per day in capacity. The reactors are modular and can be arranged with fertilizer processing equipment (i.e. dewatering, sorting, storage and bagging) to accommodate WWTPs of any

Table 19.1 Key figures of the process.

General	WASSTRIP Input Material	Waste/Surplus Activated Sludge (WAS/SAS)	–
	Pearl Input Material	WAS/SAS thickening liquor and digested sludge dewatering liquor	–
	Type of Process	Anaerobic WAS/SAS P release (WASSTRIP) and struvite crystallization (Pearl)	
Operating	Electricity demand	1.6	[kWh/kg $P_{recovered}$]
	Heat demand	3.0	[kWh/kg $P_{recovered}$]
	Chemical demand	2.4	[kg $MgCl_2$/kg $P_{recovered}$]
		0.7:1	[molar ratio Mg:P]
		0–2	[kg NaOH/kg $P_{recovered}$]
Product	Type	struvite	
	Morphology	0.9–4.5 mm pellets	
	P-concentration	12.6%	% P/DM
	P-recovery rate	45–60%	% of P in sludge input
	Distribution of the product	Distributed by Ostara, though a purchase agreement with the plant owner, to turf, ornamental, and agricultural markets	
Residuals	Phosphorus and nitrogen depleted sludge liquors		
Reference	Location	Slough, UK	–
	Scale	250,000	PE
	Start of operation	2012	–

(*Continued*)

Table 19.1 Key figures of the process (*Continued*).

Outstanding features	Combines a Pearl reactor with capacity to recover 65 kg PO4-P, and a simplified fertilizer dewatering, dryer, sorting and bagging operation in less than 150 m^2		
Reference	Location	Amersfoort, NL	–
	Scale	500,000[a]	PE
	Start of operation	2016	–
Outstanding features	Combines a Pearl, WASSTRIP, thermal hydrolysis and downstream deammonification in a single energy and nutrient recovery installation.		
Reference	Location	Madrid, ES	–
	Scale	1,200,000	PE
	Start of operation	2016	–
Outstanding features	Constructed in partnership with Veolia Water Technologies, Pearl enables the wastewater plant to use lower cost biological phosphorus removal in place of existing chemical phosphorus removal by eliminating phosphorus return streams.		
Reference	Location	Chicago, IL, USA	–
	Scale	2,300,000	PE
	Start of operation	2016	–
Outstanding features	The world's largest nutrient recovery facility, with a capacity to produce 30 tonnes of Crystal Green a day.		
Reference	Location	Portland, OR, USA	–
	Scale	500,000	PE
	Start of operation	2009	–
Outstanding features	Pearl's and WASSTRIP's longest running installation.		

[a] PE has been adjusted to reflect impact of sludge imports

size. An economy of scale means that capital and operating costs decrease with increasing population served. The values in Table 19.1 are representative for a WWTP serving a population equivalent (PE) of 250,000.

19.3 OUTLOOK – FURTHER DEVELOPMENTS

Pearl nutrient recovery technology has 49 years of cumulative operating experience at 14 facilities around the world. This experience has resulted in continuous improvements to the system design to optimize cost and operational reliability. On average Pearl facilities achieve a payback on capital investment in 3–7 years and operate with over 95% uptime.

Future developments are aimed at improving the capital cost for facilities of less than 100,000 PE, further quantifying the net financial benefit of Pearl and WASSTRIP and wastewater treatment plant operations, and developing industrial wastewater solutions.

Chapter 34

Wastewater treatment of the future: Health, water and resource protection

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34.1 INTRODUCTION

The field of supply and disposal in settlement structures is currently undergoing major changes. On the one side, the focus is on the user's supply with energy, water, and food/goods and on the other side it is on the disposal of wastewater and waste. Thereby, disposal includes recycling and disposal processes with respective treatment processes prior to recycling and disposal. In the past, via the construction of sewer systems leading to conventional wastewater treatment plants (WWTPs) as end-of-pipe solutions for treating wastewater, fundamental interests of health and water protection have been met. The spread of diseases due to lacking sewers was most widely prevented, at least in the industrial nations. With the growing knowledge that wastewater ingredients, such as carbon, nitrogen, and phosphorus, lead to silting, oxygen consumption, and eutrophication of waterbodies, wastewater treatment plants were implemented, thus increasing the quality of waterbodies significantly. However, the question is whether the objectives of sustainable wastewater treatment have been achieved this way.

Research results in the fields of health and water protection as well as changes in society's ecological awareness (climate and resource protection)

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require a new perspective regarding wastewater treatment. WWTPs for (just) "treating" wastewater will become "water and resource service providers". They will be service providers for humans (wastewater drainage and treatment) and waterbodies, (in terms of ecosystem services (Millennium Ecosystem Assessment [MEA], 2005)), energy service providers and manufacturers of demand-oriented products, e.g. water and fertilizers. Sustainable wastewater treatment consists of the following components (Schaum, 2016; Schaum & Cornel, 2016):

- *Health protection*: Safeguarding of hygienic requirements, including legionella and antibiotic-resistant germs, compliance with quality standards for bathing waters in waterbodies, supply of hygienically safe water for water reuse.
- *Water protection*: Minimization of eutrophication via nutrient elimination (phosphorus, nitrogen) to the greatest possible extent; elimination of micropollutants, microplastics and nanoparticles for the protection of aquatic fauna and from the perspective of preventive health care.
- *Resource protection*: Minimization of resource consumption for wastewater treatment, e.g. energy and operating materials; minimization of environmental impacts; resource recovery by utilizing resources contained in wastewater, particularly water, nutrients and energy.

To make all this possible, it is essential to combine technology and operation optimization, thus identifying synergy effects to be utilized.

34.2 OBJECTIVES OF WASTEWATER TREATMENT

34.2.1 Health protection

Wastewater has to be disposed of in such a way that the common good is not impaired. This guiding principle may well be considered as the fundament of wastewater treatment. This becomes obvious, particularly, when looking at the history of wastewater treatment (hygiene requirements), which, especially in the international context and in terms of safeguarding the access to sanitary facilities, is still vitally important. In addition to hygiene aspects, minimizing the input of micropollutants, nanoparticles and microplastics into the food chain is a crucial point from the perspective of (preventive) health care (Schaum & Cornel, 2016).

34.2.1.1 Safeguarding basic sanitation

In the 19th century, the construction of sewer systems enabled the drainage of wastewater from settlements to the next waterbody. The declared objective was to prevent the spreading of infectious diseases, such as cholera and typhus, by safeguarding hygienic standards in cities, cf. Cooper (2001); Tilley (2011). This proved to be successful.

In the beginning of the 21st century, health protection in the field of wastewater treatment has not lost any of its importance. Worldwide, approx. 2.6 billion (10^9) people still do not have access to basic sanitary facilities; day by day, approx. 3900 children die because of poor hygienic conditions, cf. UN (2012). Current figures show that approx. 2 billion (10^9) people do not have access to clean drinking water, cf. WHO (2017). Although most countries have introduced sanitary concepts, thus safeguarding health protection, there are still many countries where respective facilities are missing completely. To follow up the Millennium Development Goals (UN, 2012), in September 2015, the United Nations defined – in context with the 2030 Agenda for Sustainable Development (UN, 2015) – as their 6th goal to "ensure availability and sustainable management of water and sanitation for all".

34.2.1.2 Disinfection: Bathing water quality and water reuse

The objective of disinfection is to inactivate (loss of reproduction) or to reduce pathogens, i.e. bacteria, viruses, parasites, thus minimizing health risks via wastewater discharge into waterbodies. The hazards thereby depend on the type of utilization of the treated wastewater (Tchobanoglous, 2003; DIN, 2004; DWA, 2013).

Research studies in pilot scale as well as in various industrial-scale implementations – in the USA, disinfection of the effluent of WWTPs is widespread, cf. Leong *et al.* (2008) – show that by using different disinfection methods, e.g. UV irradiation, chlorine dioxide dosing, ozonation and chlorination, requirements for the microbiological discharge quality are usually met. The effluent quality depends on the characteristics of the respective treatment steps and disinfectant dosages and is a decisive criterion for whether the discharge water may be introduced into bathing waters or used for diverse reusing purposes, cf. e.g. Tchobanoglous (2003), Bischoff (2013). Besides the applied disinfection methods, the effectiveness of disinfection strongly depends on the composition of the wastewater to be treated. Suspended particles and colloids, in particular, may impair the effectiveness of disinfection and/or lead to negative disinfection byproducts (especially when applying chlorine or ozone), cf. Bischoff (2013). Therefore, upstream processes for removing solids, e.g. micro-sieves and filtration processes, are of great importance.

Presently, in Germany, the spreading of legionella in water is of particular interest. In Warstein (a small town in Northrhine-Westfalia, Germany), in 2013, 162 people came down with legionellosis, and two people died (Evers & Grünebaum, 2015). The cause lay in the effluent of a WWTP which was contaminated with legionella. In a downstream plant, river water was used as cooling water, and via the re-cooling plant legionella containing aerosols were released. Although this case showed specific boundary conditions, it proves, besides the issue of disinfectant application in re-cooling plants, once again the relevance of wastewater treatment in health protection and the need for a (further) development of respective technologies (Schaum & Cornel, 2016).

Furthermore, pathogens resistant to antibiotics are in the focus of research, whereby research in wastewater treatment is only at its beginning regarding this topic. Primary sources for the increase in antibiotic resistance are wastewaters from hospitals, municipal WWTPs, fattening plants and the food industry. Besides the application of antibiotics, emissions of biocides as disinfectants and the use of other antimicrobial agents can lead to co-selection of antibiotic resistance. WWTPs are a major secondary source, as here resistance accumulation through primary sources may occur (Kaeseberg *et al.*, 2015).

34.2.2 Water protection

The German Water Resources Act defines the requirements for a direct discharge of treated wastewater into waterbodies as follows: "A permit to discharge wastewater into waterbodies (direct discharge) may only be granted if the amount and harmfulness of the wastewater is kept as low as possible, while maintaining the procedures according to the state-of-the-art, the discharge is compatible with the requirements regarding the characteristics of the waterbodies and further legal requirements, and WWTPs or other facilities are constructed and operated that are necessary to meet the requirements." c.f. German Water Resources Act (WHG, 2009). In terms of the European Water Framework Directive, c.f. WRRL (2000), this means achieving a "good status" of waterbodies, i.e. the quality of the waterbodies approaches "natural conditions".

34.2.2.1 European water framework directive

With the beginning of the 21st century, in Europe, the approach towards water protection has changed. Whereas in the past, emission-related approaches prevailed, i.e. reduction of the discharge into waterbodies, the European Water Framework Directive (WRRL, 2000) counts on immission-related approaches, i.e. viewing the input into and impact on the environment (waterbody, animal/human). With the commencement of the European Water Framework Directive on 2000, December 21, a regulatory framework for Europe-wide comprehensive water protection was created (WRRL, 2000). The directive starts, characteristically, with the recital "Water is not a commercial product like any other but, rather, a heritage which must be protected, defended and treated as such."

Cross-border considerations of the quality of waterbodies, including entire river basins, in particular, are to be highlighted as novelty. The central issue of the European Water Framework Directive is the demand for good ecological as well as chemical quality of waterbodies by 2015 with extension to 2027 at the latest.

34.2.2.2 Minimization of nutrient input into waterbodies

Based on the contamination of waterbodies with nutrients, cf. for phosphorus Krause (2018); Withers and Bowes (2018), in Germany, significantly lower limit values for phosphorus are being discussed: For Lake Constance this means a discharge limit value of 0.3 mg/L P_{tot}; the Berlin Senate demands a value of ≤0.05 mg/L P_{tot} for the WWTP Berlin-Ruhleben, cf. Rosenwinkel and Lorey (2009); the federal state of Hesse is discussing discharge limit values of 0.2 mg/L P_{tot} (as monthly arithmetic mean) or 0.4 mg/L P_{tot} (2-h-samples) for WWTPs > 100,000 population equivalent (PE) and some plants between 10,000 and 100,000 PE, in the case of discharging into waterbodies with high pollution loads or higher susceptibility (e.g. reservoirs), cf. Cornel *et al.* (2015).

In order to guarantee these low values, usually a (membrane) filtration unit will be necessary. Even with 1–2 mg/L biomass in the effluent of WWTPs, a limit value of 0.05 mg/L P_{tot} will be exceeded, independent of dissolved inorganic and organic phosphorus compounds (e.g. also phosphonates), cf. Cornel *et al.* (2015), Barjenbruch and Geyer (2018), Baumann (2018), Bratby (2018).

34.2.2.3 Micropollutants, nanoparticles and microplastics

In the field of wastewater treatment, the focus is on several "new" substance groups, such as micropollutants (Daughton & Ternes, 1999; Deblonde *et al.*, 2011; Verlicchi *et al.*, 2012; Luo *et al.*, 2014), nanoparticles (Abels, 2012) and microplastics (AWI, 2014; Bannick *et al.*, 2015; UBA-AUT, 2015; Yang *et al.*, 2015).

Due to their mostly poor biological degradability, there is quite a range of micropollutants that are detected in waterbodies and in trace levels even in drinking water. Although there is (still) little evidence that micropollutants in waterbodies are a health risk, there is at least the connection between water protection and preventive health care, cf. Oehlmann *et al.* (2014). This means, physical processes, such as (membrane) filtration, adsorption to activated carbon, and/or chemical processes, such as oxidization with ozone, are additionally required.

34.2.2.4 Substance prohibition for water (and health) protection

Along with the implementation of wastewater treatment, regulatory as well as technical measures have been introduced and international regulations, e.g. Stockholm Convention on Persistent Organic Pollutants, have been agreed on, in order to prevent the introduction of poorly degradable or removable substances into wastewater. In addition, there are bans on substances, e.g. eutrophying softeners (polyphosphates) in detergents (ATV, 1997; Klöpffer & Scheringer, 2000).

For micropollutants, as well, comparable approaches are being discussed. In Germany as well as in other countries, there are discussions in progress on regulatory measures for the prohibition of microplastics in cosmetics and personal care products.

34.2.3 Resource protection

UBA (2012a) defines resource protection as all measures to conserve or recreate natural resources. "(…) [This] includes renewable and non-renewable primary raw materials, physical space (such as land), environmental media (water, soil and air), flow resources (such as geothermal, wind, tide and solar energy), and the diversity of all living organisms" (UBA, 2012a).

34.3 RESOURCES IN WASTEWATER: WATER, NUTRIENTS AND ENERGY

34.3.1 Water

Wastewater consists of more than 99% water, making water the quantitatively largest resource. Although in Germany, water of sufficient quality and amount is available, the question of water reuse even in regions with currently abundant water resources still remains, in particular in the context of local and seasonal availability (BMBF, 2014), in the future intensified by climate change, and in view of the availability of water worldwide. In the future, approaches including the reuse of treated wastewater in combination with advancements in municipal wastewater treatment will become more important. Along with a shift of rainy seasons towards winter, i.e. outside the vegetation period, and due to the cultivation of plants for biogas generation, the application of water reuse in agriculture will gain in significance. Furthermore, the manifold water reuse processes in industry are to be considered, state-of-the-art already today and with economy as the driving force.

Water and energy are directly linked: Water is needed for the supply of energy, e.g. for cooling. At the same time, the utilization of water requires the input of energy. Regarding urban water management, the heating of water is the main factor. Depending on the quality of the raw water, the supply of drinking water requires different treatment processes, whereby energy consumption increases with increasing treatment steps (from basic mechanical processes as far as reverse osmosis). As the water demand, especially in metropolitan areas, exceeds its availability, long-distance pipelines are needed with respective increased energy consumption (Schaum & Cornel, 2016).

Accordingly, water reuse may prove as an important contribution towards the conservation of water and energy resources. As most times, water required for water reuse is locally available, long-distance transport pipes are not needed. By adjusting the treatment processes to the application goal (fit for purpose), energy demand can be minimized, cf. Schaum *et al.* (2014), Schaum (2016).

34.3.2 Nutrients

At a very early stage, sprinkler irrigation of wastewater was one of the first applications of water reuse, in which the nutrients contained in wastewater were utilized. Since then, respective hygiene questions have gained importance step-by-step. Along with the construction of sewer systems, the first stonewalled sewage pits were built at the beginning of the 19th century. Feces were carried away to be used as agricultural fertilizers. Along with the upgrading of wastewater treatment, sewage sludge treatment advanced. Already back in 1907, Karl Imhoff developed the Imhoff tank (Emscherbrunnen). Subsequently, the first heated digesters for sewage sludge stabilization were constructed.

With change in the society's ecological awareness, sewage sludge recycling changed as well, especially in view of sewage sludge as a nutrient and a pollutant sink. In some countries, for example Germany, Switzerland or the Netherlands, sewage sludge disposal shifted from dumping, landfilling, landscaping/agriculture to incineration. Thereby, the above-mentioned aspects of health and water protection apply accordingly for sewage sludge treatment/recycling (UBA, 2012b; Kunkel & Ternes, 2014; UBA, 2015).

Phosphorus is a limited, vital resource that cannot be substituted by any other element, cf. Adam and Krüger (2018), Udert (2018). The main field of application is the fertilizer industry and agriculture. During wastewater treatment, phosphorus is incorporated into sewage sludge via biological as well as chemo-physical processes (precipitation). There are various approaches to recover phosphorus from wastewater, sewage sludge and sewage sludge ash, necessitating the separation of nutrients from pollutants. There are technologies for phosphorus recovery in WWTPs to be implemented at various stages, i.e. the treatment of wastewater, sewage and sewage sludge ash, c.f. Schaum (2018).

In October 2017, in Germany, the amendment of the Sewage Sludge Ordinance (AbfKlärV) that regulates the application of sewage sludge in agriculture was enacted (AbfKlärV, 2017). Besides the question of thermal sewage sludge recycling (incineration), the focus is on regulatory instruments for phosphorus recovery. With the coming into force of the amendment, the operators of German WWTPs face major challenges in the coming years. In addition to a tightening of the limit values for soil-based sewage sludge utilization, e.g. for organic pollutants, both in sewage sludge and in soils, the introduction of an obligation for the recovery of phosphorus from sewage sludge is a significant innovation. The following parameters must be observed: The remaining phosphorus content in sewage sludge must be less than a threshold of 20 g P/kg TS (Total Solids). Alternatively, the efficiency of phosphorus recovery bust be at least 50%. The implementation affects WWTPs > 100,000 PE with a transitional period of 12 years and WWTPs > 50,000 PE with a transitional period of 15 years (AbfKlärV, 2017). In Switzerland and the Netherlands, as well, there are discussions on the implementation of legal frameworks for phosphorus recovery.

Although nitrogen is virtually limitless when supplied via the atmosphere, the generation of nitrogen fertilizer implies a high energy demand. Nitrogen contained in wastewater/sewage sludge may prove an alternative, as long as it can be utilized (in agriculture) with low energy requirements, cf. Schaum and Cornel (2013).

34.3.3 Energy

In Germany, along with the amendment of the Waste Water Ordinance (AbwV, 2014), energy efficiency and energy potentials have been included into the regulatory framework: "Wastewater treatment plants have to be constructed, operated, and used in such a way that an energy-efficient operation mode is enabled. Energy potentials generated by wastewater treatment have to be utilized, insofar as they are technically feasible and economically justifiable." Regarding future wastewater treatment, this means – even in the case of energy demand increases due to additional process technology for the elimination of micropollutants and for disinfection – minimizing the use of energy and, at the same time, utilizing the energy contained in wastewater. Besides the utilization of the thermal energy contained in wastewater, the focus should also be on the utilization of the energy stored in carbon compounds.

34.3.3.1 Chemically bound energy in wastewater: Evaluation via COD balancing

During wastewater treatment, carbon compounds, analytically determined via the chemical oxygen demand (COD), are, on the one hand, converted to carbon dioxide and water and, on the other hand, eliminated from wastewater via sewage sludge (primary and surplus sludge), cf. Schaum *et al.* (2015b). There are residual concentrations that are not removed, but discharged into the waterbody, cf. Svardal (2012); Schaum (2016). From the point of view of sustainable resource efficiency, carbon contained in wastewater should be used as chemically bound energy, e.g. conventionally via the conversion of carbon compounds into digester gas with subsequent use in combined heat and power units (CHP) for generating electricity and heat or via thermal recycling of sewage sludge.

The COD is the key parameter for assessing the chemically bound energy, as the energy potential in wastewater and sewage sludge can be directly calculated via stoichiometry (Schaum, 2016):

$$\text{Lower heating value } H_U\,[\text{kJ/kg TS}] \text{ or } [\text{kWh/kg TS}] = 12.56 \text{ or } 3.49 \cdot C_{COD}$$
$$\text{with } C_{COD} \text{ in } [\text{g COD/kg TS}]$$

For the balancing and dimensioning of sewage sludge treatment plants, the COD can be used due to stoichiometry, being thereby independent of the respective substrate (sewage sludge, co-substrates), in contrast to approaches based on the organic substance/total volatile solids (TVS), which are only valid for constant/comparable COD/TVS ratio (e.g. exclusively for sewage sludge).

34.3.3.2 Sewage sludge treatment plants in interaction with the energy industry

A key component of energetic optimization of sewage sludge treatment plants was (and still is) the development and implementation of energy analyses, in Germany, in particular, from the late 1990s. Practical applications show that energetic optimization is already possible by looking at the status quo and the comparison/assessment with key figures (benchmark-data). Besides process adjustment of subsystems (e.g. control of oxygen transfer, adjustment of the (seasonal) solids content in the biological treatment unit and of the existing mechanical equipment) optimization is also enabled via the application of new, highly-efficient machinery. In principle, the basis of energy analyses is the static system analysis of annual mean values, cf. DWA (2017)

The needs-oriented supply and storage of energy as well as the balancing of peak loads in the energy grids, in particular electricity, caused by temporary and regional differences between energy generation and demand is one of the major challenges of our time. There are various operation strategies for flexibilization:

- Load management (Demand-Side-Management), which is already (partly) implemented in practice, aims at balancing the daily electricity demand and generation to the greatest possible extent.
- Tariffs for electricity in the short-term electricity markets (day-ahead or intraday) are subject to severe fluctuations, whereby the cost structure is changing due to the volatility of renewable energies. By participating in the spot markets, electricity is purchased at low tariffs, and, accordingly, at high tariffs, the electricity demand is covered via self-supply.
- The supply of balancing energy is necessary to compensate imbalances between the generation and demand of electricity. The cooperation is hereby realized via a virtual power plant with other providers from the electricity balancing market.

One example for effective control of energy production is the flexibilization of digester gas production via raw sludge and co-substrates (organic substances that are generally readily degradable, e.g. expired food). Co-substrates can be fed demand-based into the digester if it has free capacities, cf. Lensch *et al.* (2015). This applies to digesters in large parts of Europe and the USA, as they were oversized in the past. The additional feed of high-energy substrates increases the digester gas and thus energy production as needed (Water Environment & Reuse Foundation [WERF], 2018). Depending on the feeding (dosing amount and frequency) of raw sludge and co-substrates, the production of digester gas can be controlled selectively (Lensch *et al.*, 2015). The chemically bound energy in sewage sludge and co-substrate becomes an energy storage, whereby co-substrates with easily degradable ingredients, in particular, are predestined for peak load situations. Table 34.1 shows the different energy densities of fossil fuels, raw sewage sludge (primary and surplus sludge), digester gas, and conventional accumulators/batteries with regard to the supply of energy.

Table 34.1 Comparison/estimation of specific energy densities of fossil fuels, raw sludge, co-substrates, and accumulators (batteries) with regard to the supply of energy (Schaum & Cornel, 2016).

		Calorific Value		**Specific Energy Density (Electricity)**	
		[MJ/kg]	**[kWh/kg]**	**[kWh$_{el}$/kg]**	**[kWh$_{el}$/m^3]**[l]
Hard Coal		31.7[a]	8.9	3.4[b]	4590
Fuel Oil		42.8[a]	11.9	4.7[c]	4000
Natural Gas		45.4[a]	12.7	7.6[d]	6.1
Primary Sludge	*TS*[e]	*16.4*	*4.6*	*0.8*[f]	
	OS[e]	1.1	0.3	0.05	50
Excess Sludge	*TS*[e]	*14.3*	*4.0*	*0.4*[g]	
	OS[e]	1.0	0.3	0.03	30
Co-Substrates	*TS*[e]	*21.0*[h]	*5.9*	*1.1*[i]	
	OS[e]	4.2	1.2	0.2	200
Biogas (from Digester)		19.3	5.4[j]	1.6[j]	1.9
Ni-Cd-Battery		–	–	0.04[k]	
Lithium-Ion-Battery		–	–	0.1[k]	130[m]

[a] Cerbe and Wilhelms (2008).

[b] Assumption for the efficiency of a coal-fired plant: 38%.

[c] Assumption for the efficiency of an oil-fired power plant: 40%.

[d] Assumption for a gas and steam co-generation plant with an efficiency of 60%.

[e] TS: based on total solids; OS: based on original substance; Assumption of TS concentration in the storage tank for the digestion, primary and excess sludge: 7% TS; Co-substrate (expired food): 20% TS.

[f] Production of biogas 340 NL CH_4/kg TVS_{in} (Zeig, 2014); TVS = 75%; Calorific value of methane approx. 10 kWh/m^3; Density of methane 0.72 kg/m^3; Electrical efficiency coupled heat and power plant (CHP) 30%.

[g] Production of biogas 170 NL CH_4/kg TVS_{in} (Zeig, 2014); TVS = 72%; Calorific value of methane 10 kWh/m^3; Density of methane 0.72 kg/m^3; Electrical efficiency CHP 30%.

[h] Measured value, average of 2 measurements (samples of 2 different substrates).

[i] Production of biogas 400 NL CH_4/kg TVS_{in} (Zeig, 2014); TVS = 90%; Calorific value of methane 10 kWh/m^3; Density of methane 0.72 kg/m^3; Electrical efficiency CHP 30%.

[j] 60–70% by volume methane or 6.0–7.0 kWh/Nm^3 biogas; Density at 65% methane: 1.2 kg/Nm^3 (DWA, 2010); Electrical efficiency CHP 30%.

[k] ETH (2003).

[l] Assumption: Hard coal 1350 kg/m^3; Fuel oil 850 kg/m^3; Natural gas 0.8 kg/m^3; Sewage sludge 1000 kg/m^3; Biogas 1.2 kg/m^3.

[m] Fieger (2015).

Though it can be clearly seen that fossil fuels have the highest energy density, the comparison with accumulators (batteries) also shows that the storage of chemically bound energy in the form of primary, surplus sludge and co-substrates with energy densities of 0.03–0.2 kWh_{el}/kg is on a comparable level. However, one has to take into account the time availability (speed of power delivery). In addition, the density of natural and digester gas has to be considered, the volume of which could be reduced via respective (high) pressure tanks. Even though the development of accumulators is currently in the focus of international research and though it is expected that capacity and energy density will increase, it is nevertheless apparent that the utilization of chemically bound energy will still play an important role in future energy management.

34.4 WASTEWATER TREATMENT PLANTS OF THE FUTURE: FROM TREATMENT PLANT TO (SYSTEM) SERVICE PROVIDER

By merging the protection of health, water and resources, WWTPs will change their scope from (just) wastewater treatment to become (system) service providers:

- *Service wastewater treatment and water protection*: Safeguarding of wastewater drainage from settlement structures and wastewater treatment to the greatest possible extent in order to protect the receiving waterbodies. Wastewater treatment is one key component in guaranteeing the ecosystem services of waterbodies (basic, supply, control and cultural services, c.f. MEA (2005)).
- *Energy system service provider*: Interaction with energy industry in the role of energy consumer, producer and storage.
- *Manufacturer*: Provision of water and fertilizers.

WWTPs as end-of-pipe facilities play an important role in the recycling economy. New concepts in urban water management can contribute significantly, as well. With the new task of “resource protection”, operators of wastewater treatment will face a new self-image. Compliance with quality standards, product acceptance, availability, performance bonds, etc. will be prerequisite for the commercialization of process and irrigation water, fertilizers, and raw phosphate substitutes as well as heat and electricity. Services and products have to be aligned strategically according to the demand (e.g. waterbodies, energy industry, agriculture), not because of the developed technologies (from push to pull). The elaboration of solutions, therefore, induces interdisciplinary cooperation, e.g. with ecotoxicologists (Prasse *et al.*, 2015), operators of energy grids and virtual power plants (Schaum *et al.*, 2015c), and the fertilizer industry (Petzet, 2013). New models regarding inter-municipal cooperation and organizational structures as well as business models might become necessary.

Especially within the field of phosphorus recovery various obstacles exist – in particular, the uncertainties concerning the utilization of the phosphorus recyclates (P-recyclates) represents a special and much discussed question. Figure 34.1 shows the result of a survey within the framework of a workshop in Germany in order to assess the responsibilities for the operation and distribution of P-recyclates. It can be clearly seen that, above all, private recycling companies were named, cf. Demmelbauer *et al.* (2018). In contrast, lesser importance concerning the responsibility for marketing is attributed to operators of WWTPs, reflecting the traditional understanding of wastewater treatment. Thus, it certainly remains interesting in which direction these questions will develop in the future. At the same time, it is also evident that the evaluation of new procedures has many other aspects, which also require new evaluation procedures, cf. Ansmann *et al.* (2018).

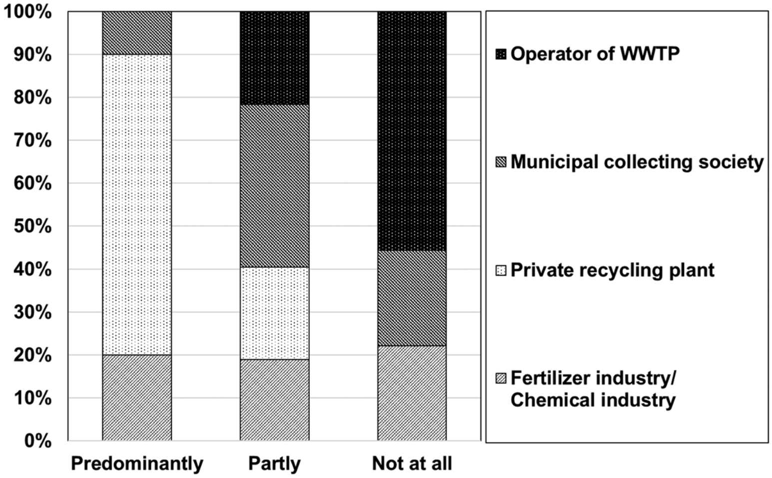

Figure 34.1 Assessment of the responsibilities for the operation and the distribution of P-recyclates, cf. Demmelbauer *et al.* (2018).

An important parameter for the future utilization of P-recyclates is the achievable price, especially in comparison to conventional phosphorus fertilizers, cf. Egle *et al.* (2018). Figure 34.2 represents an assessment of the price development from a survey, cf. Demmelbauer *et al.* (2018). Although a heterogeneous overall picture emerges, there is still a great deal of skepticism as to when and whether the prices of P-recyclates and conventional P-fertilizers will converge. The assessment is also based on the fact that many processes for P-recovery have currently reached the pilot phase, but reliable figures for continuous operation are only conditionally available – except for the struvite process.

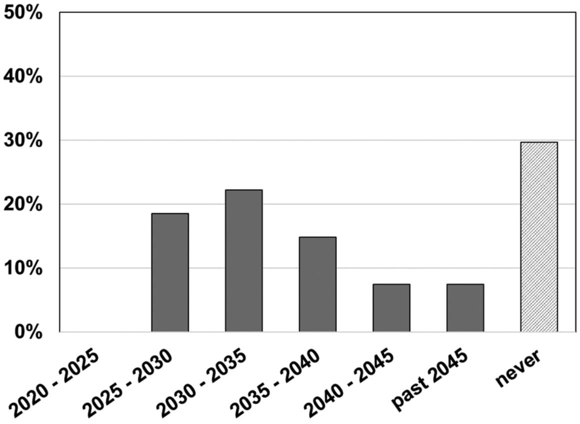

Figure 34.2 Period during which prices for phosphorus-based recycled and conventional phosphorus fertilizers will converge (assessment).

34.5 CONCLUSION AND OUTLOOK: FROM TREATMENT FACILITY TO SYSTEM SERVICE PROVIDER

Supply and disposal of water is one of the integral components of settlement structures. This can be seen very clearly in situations where due to water scarcity and lacking sanitary facilities people die or fall ill every day.

Regarding the demands for sustainable wastewater treatment, specific technologies are to be (further) developed and implemented in order to meet the requirements for health, water and resource protection. Hereby, questions of economy, ecology (Schaum *et al.*, 2015a), technology/operation, and society have to be taken into account. The focus of future developments is on the following topics (Schaum & Cornel, 2016):

- *Health protection*: Compliance with hygienic requirements, disinfection measures regarding waterbodies as well as water reuse, retention of antibiotic-resistant germs.
- *Water protection*: Protection against eutrophication, nutrient elimination to the greatest possible extent, elimination of micropollutants, microplastics and nanoparticles.
- *Resource protection*: Resource-efficient operation (fit for purpose), utilization of resources contained in wastewater (water, nutrients, energy), climate protection in terms of minimizing the emission of greenhouse gases.

On a-case-by-case basis, there have to be discussions on the cost-benefit ratio, risk factors and the necessity of removing selective substance groups. However, within the scope of sustainable planning, all potentially upcoming requirements are to be considered before deciding on specific technologies that might solve an acute problem, but block and hinder the path to respond on challenging future needs. In particular, the decision for specific technologies should include questions of synergy effects. For example, the advanced retention of the solids content is a prerequisite for achieving objectives to be expected in future applications (advanced phosphorus recovery, retention of microplastics, elimination of micropollutants, disinfection). Questions of protecting health, waterbodies/soil and resources have to be included in sewage sludge disposal/recycling, as well, in analogy to wastewater treatment.

With the new task of "resource protection", operators of WWTPs, or "Water Resource Recovery Facilities (WRRFs)" as it is meanwhile called in the USA, will face a new self-image. Wastewater treatment plants are changing from (just) treating wastewater to becoming (system) service providers. This involves wastewater drainage/treatment for settlement structures on the one hand, but also the "service" for the waterbodies. Via the interaction with the energy industry and the provision of fertilizers and water, there will be new tasks in wastewater treatment. This includes questions of marketing, compliance with quality standards, product acceptance, availability, performance bonds, etc. There is a cross-system linkage among wastewater treatment, urban drainage, waste and energy management, as well as agriculture. In future, synergy effects are to be (further) exploited in such a way that WWTPs become an integral part in the supply and treatment/disposal system of settlement structures.

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