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# Chapter 1

# Resource recovery from municipal wastewater: what and how much is there?

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## 1.1 INTRODUCTION

The introduction of sewer networks for the safe collection and subsequent treatment of municipal wastewater at down-stream wastewater treatment plants has had a major impact on public health and the protection of the aquatic environment. It is often identified as one of the ten great public health achievements of the 20th century [1]. To achieve this, management and engineering practice has always had a strong focus on treating wastewater by removing pollutants. The most well-known and most widespread approach to achieve effective pollutant removal is the conventional activated sludge process, which recently celebrated its 100-year anniversary [2]. Despite successfully protecting human and environmental health during the 20th century, traditional removal-focused approaches for domestic wastewater treatment will not suffice in the 21st century, as broader environmental and economic consequences of this mentality become increasingly well understood. The recovery of resources embedded within the wastewater matrix, without compromising human health and environment protection, represents an alternative fitting within a circular economy context. Municipal wastewater contains a wide range of resources in addition to water, albeit at relatively low concentrations. Nutrients (mainly nitrogen and phosphorus), dissolved organics, coagulants, cellulose and potentially other valuables such as metals, proteins and polysaccharides, could be recovered. The reuse of water has the potential to alleviate water scarcity, while recovered nutrients and organics can be valorized as fertilizer, feed, energy or higher value products for various industrial sectors. It is not the aim of this chapter to discuss these in detail, but to provide the reader with a general overview of the different resources contained in municipal wastewater. The current and potential recovery of these resources is also addressed. It should be noted that the composition of municipal wastewater differs to some extent in terms of concentrations of constituents, local availability and

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value of contained resources. The factors/characteristics causing this variability are briefly discussed in this chapter as well. As a final major remark, when considering resource recovery from municipal wastewater, the presence of pathogens, toxic compounds, waterborne viruses and other impurities cannot be ignored. The challenges arisen by the presence of these pollutants are, however, beyond the scope of this chapter.

## 1.2 LEARNING OBJECTIVES

At the completion of this chapter you should be able to:

- Describe the magnitude of municipal wastewater generation and treatment and understand its potential for resource recovery.
- Summarize the different factors affecting the composition and volume of municipal wastewater and its impact on resource recovery potential.
- Describe the key resources that can be recovered during the treatment of municipal wastewater that are *present* in or *added* during the treatment of municipal wastewater.
- Understand how centralized and decentralized municipal wastewater treatment systems impact the potential for resource recovery.
- Understand that resource recovery at municipal wastewater treatment plants is not a 'one size fits all' concept.

## 1.3 HOW DO WE DEFINE WASTEWATER?

Sewage, domestic or municipal wastewater all relate to wastewater originating from domestic use, and can be defined as '*the water supply of the community after it has been used in a variety of applications and which now contains constituents that render it unsuitable for most uses without treatment*' [3]. It mainly consists of a mixture of human excrements and wastewater originating from municipal toilet use, cleaning, washing and cooking. For simplicity, this mixture will be referred to as 'municipal wastewater' in this chapter. Other wastewaters, such as industrial wastewater, are discussed elsewhere in this book. Despite the fact that the composition can vary to some extent (see section 1.6), a key feature of municipal wastewater is that, except for the water itself, resources are present at low concentrations, which often complicates their efficient recovery.

## 1.4 HOW MUCH MUNICIPAL WASTEWATER IS PRODUCED?

It is estimated that 312 million megaliter (ML) of municipal wastewater is produced annually, of which 187 million ML is treated, equaling to about 60% of the total [4]. This is most likely an underestimation, as accurate data from highly populated and fast-growing developing countries is not available. It is not the aim of this chapter to provide detailed data on the amounts and differences in the daily production of municipal wastewater in different countries, but the following example is shown to illustrate that the amount of municipal wastewater produced per capita can differ substantially between countries. The average volume of wastewater produced per capita (arriving at the wastewater treatment plants (WWTPs)) in the USA is almost 690 L/day [5, 6], while in Belgium (Flemish region) this value is only about 378 L/day (data: Aquafin Inc., Aartselaar, Belgium). Interestingly, this relates to some 110 L/day of residential water consumption per capita in Belgium, hence the remaining 268 L originates from other sources such as run off, commercial and governmental buildings and industrial wastewater streams discharged into the sewer network (data: Aquafin Inc).

## 1.5 HOW IS MUNICIPAL WASTEWATER COLLECTED?

In developed countries and urbanized regions, wastewater treatment is generally centralized: municipal wastewater is transported via a complex network of underground sewers to a central WWTP for its

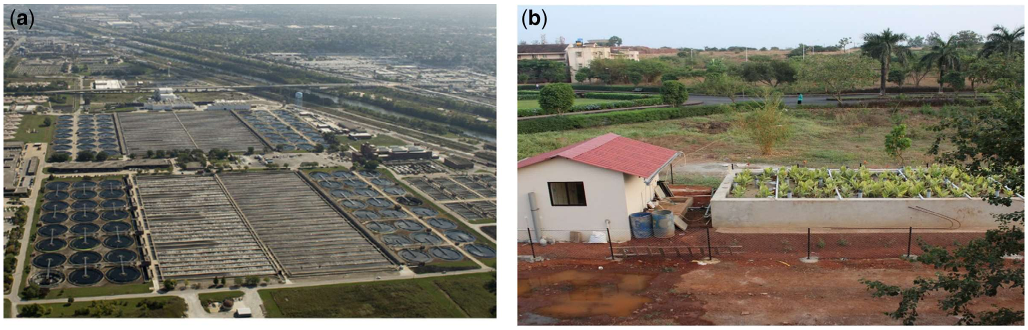

**Figure 1.1** (a) Centralized wastewater treatment plant: The Stickney Water reclamation Plant, adapted from Metropolitan Water Reclamation District of Greater Chicago, 2018 [7]. (b) Decentralized wastewater treatment plant by constructed wetlands [8].

treatment prior to discharge into the receiving environment. In combined sewer systems, run-off and rainwater are collected together with domestic (and industrial) wastewater. In sanitary sewers, municipal wastewater is collected separately. Sanitary sewers are becoming increasingly dominant, as legislation is fading out the use of combined sewers. However, many cities still continue to use combined sewer systems. It is important to realize that in major urbanized areas, most of the municipal wastewater produced is treated in a few large WWTPs, with capacities often ranging between 100 000–1 000 000 population equivalents (PE), and even up to multiple million PEs. For example, the Stickney wastewater treatment plant in Chicago (USA, Figure 1.1(a)) has a maximum capacity of 2 300 000 PE, treating about 5451 ML/day under storm weather flow conditions [7]. One can imagine that the scale of the WWTP has a substantial impact on the economy of scale of resource recovery activities and the potential to recover resources at a practical relevant scale. In remote, less densely populated areas and developing countries, access to centralized sanitation infrastructure is often lacking, and smaller, decentralized, treatment concepts such as constructed wetlands (Figure 1.1(b)) are more common due to the lower investment costs when compared to centralized infrastructure. Smaller size WWTPs and decentralized systems have varying capacities, and can be used to treat wastewater from a single house or from several thousand PEs. Smaller scales often create additional burdens on the economics of resource recovery, given the inefficiencies and challenges of managing decentralized systems, and the low mass flows of resources that can be potentially recovered.

## 1.6 UNTREATED MUNICIPAL WASTEWATER – WHAT RESOURCES ARE IN THERE AND IN WHAT CONCENTRATION RANGE?

Water is the dominant component of wastewater with typically more than 99% of municipal wastewater comprised of water itself. Besides water, household municipal wastewater is primarily a mixture of feces, organic kitchen wastes, urine and water originating from cleaning, washing and cooking. At a household level, municipal wastewater can be identified as three separate streams, namely, black, grey and yellow water, which are typically collected together. Black water refers to a mixture of feces, urine, and flush water, and is characterized by high concentrations of organic matter, nitrogen and phosphorus. Grey water, which comprises water from cooking, washing and cleaning, is more dilute and represents most of the wastewater flow. Urine is occasionally collected separately as yellow water. Table 1.1 provides a summary of the typical relative contributions of waste streams generated at the household level to the total wastewater mass flow. The typical concentrations of various components found in each stream are also presented.

The varying flow rates and composition of the individual waste streams determine the characteristics of the raw wastewater as it enters the sewer system. The amount and characteristics

**Table 1.1** Typical relative contributions of some of the major components embedded in domestic wastewater, expressed as percentage of total mass flow. Average concentrations of main components are also presented [9].

| Parameter | Grey water | Urine | Feces |
|---|---|---|---|
| Typical daily flow (L/capita/day) | 108 | 1.2[a] | 0.2[a] |
| Contribution to overall Flow rate (%) | 99 | 0.9 | 0.1 |
| Contribution to overall COD (%) | 50 | 11 | 31 |
| Contribution to overall nitrogen (%) | 8 | 79 | 13 |
| Contribution to overall phosphorus (%) | 28 | 47 | 25 |
| Contribution to overall potassium (%) | 7 | 71 | 22 |
| Water content (%) | 99 | 95 | 77 |
| COD[b] (mg/L) | 620 | 10 236 | 155 000 |
| $BOD_5$[c] (mg/L) | 279 | 4567 | 60 000 |
| Total nitrogen (mg/L) | 23 | 8661 | 7500 |
| Total phosphorus (mg/L) | 8.5 | 732 | 3000 |
| Potassium (mg/L) | 10 | 2047 | 4500 |

[a] *Mass flow, expressed in g/capita/day.*

[b] *COD refers to chemical oxygen demand and represents the total amount of oxidizable matter present in the wastewater.*

[c] *$BOD_5$ refers to biological oxygen demand and comprises the biodegradable fraction of the oxidizable matter (tested in 5 days at 20°C).*

of the grey water produced can substantially differ between countries, depending highly on local habits, and can be substantially higher than earlier mentioned numbers. A first factor affecting the volume and composition of wastewater is the volume of drinking water consumed. High per capita consumption of drinking water generally results in higher flow rates and more dilute wastewaters, except where other organics are introduced into the water (e.g., via kitchen grinders or in catchments where industrial trade waste enters the sewerage system). Additionally, the carbon and nutrient contents are influenced by local diets and caloric intake. Specifically, nearly all (99–100%) the nitrogen and phosphorus that is ingested is excreted in urine and feces, whereas a smaller fraction of caloric intake (2–10%) is ultimately excreted [10]. In general, in higher income countries the water consumption and nutrient excretion rates per capita are higher than in developing countries and communities. Even among the more developed countries, the differences can be substantial. Because of these differences, the concentrations of nitrogen in urine can differ significantly, with reported values ranging between 2.6 to 16 g total N/L, respectively [9]. It is important to note that in fresh urine most of the nitrogen is fixed as urea. Urea subsequently gets hydrolyzed into ammonium ($NH_4^+$) by enzymes produced by bacteria present in biofilms on the walls in the storage and collection systems. Therefore, the nitrogen load of municipal wastewater arriving at WWTPs typically comprises around 75–90% ammonium. Factors such as cleaning/washing habits, level of urbanization, and drinking water price also affect the wastewater composition and volume. As an example, in countries such as Japan or in regions like the Middle East, the use of toilet paper is either prohibited or not customarily used. As a consequence, the amount of organic matter in wastewater in these countries is substantially lower [11]. In addition to the above-described human aspects, climate and meteorological phenomena also affect the composition of the collected wastewater. In combined sewer systems (collecting run-off from precipitation) or when intrusion of sub-surface waters into sewer systems plays a significant role, wastewater volumes increase and concentrations decrease during precipitation events or wet weather seasons [12]. Rainfall patterns can thus have a substantial impact on the wastewater composition. However, it should be noted that in moderate

**Table 1.2** Typical composition of raw municipal wastewater in terms of major compounds, adapted from Metcalf and Eddy [3].

| Parameter | Low strength | Medium strength | High strength |
|---|---|---|---|
| COD total (mg/L) | 500 | 750 | 1200 |
| COD soluble (mg/L) | 200 | 300 | 480 |
| $BOD_5$ (mg/L) | 230 | 350 | 560 |
| Volatile fatty acid (VFA) (mg-acetate/L) | 10 | 30 | 80 |
| Total nitrogen (mg/L) | 30 | 60 | 100 |
| Total Kjeldahl nitrogen (Ammonia-N + organic-N) (mg/L) | 30 | 60 | 100 |
| Ammonia-N (mg/L) | 20 | 45 | 75 |
| Total phosphate (mg/L) | 6 | 15 | 25 |
| Total suspended solids (TSS) (mg/L) | 250 | 400 | 600 |
| Volatile suspended solids (VSS) (mg/L) | 200 | 320 | 480 |

climates such as Europe and the USA, dry weather flow conditions typically prevail about 95% of the time. The effect of precipitation also interacts with the effect of urbanization due to, for example, impermeability of the soil in dense urban areas.

While the composition of municipal wastewater thus fluctuates between different locations in the world, municipal wastewater is a waste stream in which resources that potentially can be recovered are generally present in low concentrations, except the water itself (which is a recoverable resource i.e. often at a high concentration). Table 1.2 shows the typical composition and concentration range of the major components present in untreated municipal wastewater.

## 1.7 WHAT RESOURCES CAN BE RECOVERED DURING TREATMENT OF MUNICIPAL WASTEWATER?

As discussed in section 1.5, municipal wastewater is typically treated in a centralized manner. The majority of municipal wastewater is currently treated by the activated sludge systems such as nitrification/denitrification with chemical P removal and enhanced biological phosphorus removal (EBPR) [13–15]. It is important to highlight that configurations of these treatment systems may vary considerably. A simplified representation of a typical flow sheet of a centralized WWTP for biological nutrient removal by means of nitrification/denitrification coupled with chemical P removal is depicted in Figure 1.2. In the figure, the major fractions and mass flows of notable resources embedded in the wastewater matrix within the different compartments of the WWTP assuming typical influent concentrations for mid-strength sewage (see Table 1.2) are shown. The figure shows that a major fraction of the incoming reactive nitrogen is dissipated and emitted to the atmosphere as $N_2$ (g), with only about 30% being assimilated in sludge. Organics and other suspended solids are removed in a primary settler, resulting in primary sludge. In the activated sludge process part of the organic matter is oxidized to $CO_2$. The surplus biomass produced during the activated sludge process is removed in a secondary settler as secondary sludge. Biogas produced via anaerobic digestion can be used for the production of electricity and heat in a combined heat and power unit. The digestate leaving the reactor is dewatered through processes such as centrifugation and belt press where biosolids and reject water are produced. The reject water contains high(er) concentrations of $NH_4$-N and $PO_4$-P which opens up opportunities for their recovery.

There are more resources that can be recovered than those depicted in Figure 1.2. In this context, a summary of potential resources that can be recovered from municipal wastewater, including the product characteristics of resources recovered and examples of their potential end-use in various

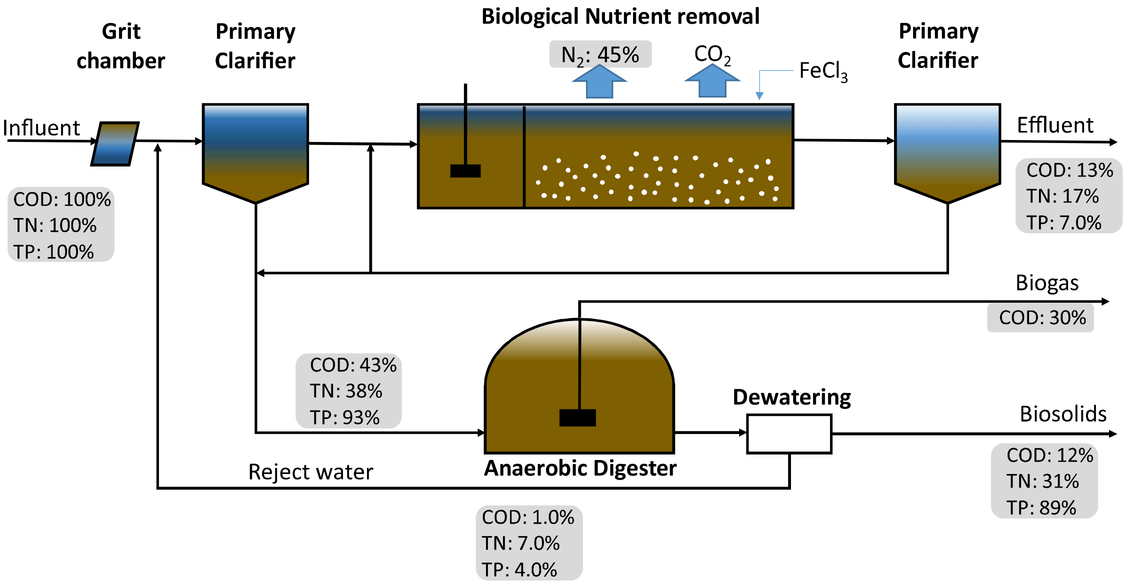

**Figure 1.2** Example of a typical flowsheet of a centralized wastewater treatment plant for biological nutrient removal and the mass flows of COD, N and P. Note that the provided values should be considered as indicative only.

market segments, is provided in Table 1.3. An important emphasis to make is that the recoverable amounts depend on multiple aspects such as wastewater composition, the specific design and treatment capacity of the WWTP, the type, efficiency of the equipment used and mode of operation and so on. Equally important, some of the products listed in the table would require specific treatment steps that in fact would exclude the recovery of other components. For example, the recovery of cellulose through a micro-sieve step reduces the biogas production potential during anaerobic digestion (i.e., cellulose comprises a substantial fraction of the incoming COD load of a WWTP). Various other examples can be mentioned within this context with the key message being that the type and amount of resources that can be recovered depend on the treatment approach installed and priorities set forward by the wastewater utility regarding the preferred resources to be recovered. In the sub-sections below, we will discuss some of the key resources that can be recovered from municipal wastewater during its treatment in more detail.

### 1.7.1 Water reuse

First and foremost, one should appreciate the fact that over 99% of municipal wastewater comprises the water itself. This can be reused for various applications, depending on the local requirements and the quality of the produced recycled water. Water reuse practices can be classified into two main categories: non-potable and potable water reuse. The most common applications of non-potable recycled water include: agricultural irrigation, landscape irrigation, industrial reuse and groundwater recharge. Among them, agricultural and landscape irrigation are widely practiced worldwide, and have well-established health protection guidelines and agronomic practices [18, 19]. About 66% of the global population currently lives in water-stressed regions and 500 million people live in areas where water consumption exceeds local renewable water sources by a factor of two. Wastewater is increasingly being considered as an important water source for the production of drinking water [20]. This can be done indirectly through the recharge of water bodies used for drinking water production

**Table 1.3** Overview of the potential resources that can be recovered from municipal wastewater and examples of their potential end-use in various market segments.

| Resource category | Resource | Recovery potential | Examples of potential end-use/market segment |
|---|---|---|---|
| Water | Water | 100–400 L/capita/day (daily water consumption substantially fluctuates depending on country/region) | Irrigation, non-potable domestic use, industrial use, potable domestic use. Injection to mitigate saltwater intrusion and so on. |
| Inerts | Sand | In the order of 0.1–3 kg/capita/year [16] | Construction industry |
| Organics | Cellulose | In the order of several kg/capita/year [11] | Biochemical industry, construction material |
| | Biosolids | It is nearly impossible to provide accurate numbers on the recovery potential of these compounds as the latter depends on a multitude of factors. 'Ball-park' figures that can be used are in the order of several kilograms per capita per year for each of these resources | Agriculture |
| | Alginate like substances | | Pharmaceutical and food industry |
| | Biochar | | Agriculture |
| | Volatile fatty acids | | Biochemical industry |
| | PHA | | Bioplastics/Agriculture |
| Energy | Biogas, as electricity[a] | In the order of 250 MJ/capita/year (theoretical)<br>In the order of 33 MJ/ capita/year (practical) | Reuse onsite, local power grid |
| | Thermal energy (heat)[a] | In the order of 760 MJ/capita/year (theoretical)<br>In the order of 291 MJ/capita/year (practical) | District heating/cooling |
| Nitrogen | Ammonia ($NH_3$) | 1.6–7.4 kg N/capita/year [10] | Power generation (Denox) |
| | Ammonium sulfate | | Agriculture |
| | Microbial protein | | Agrifood, aquaculture |
| | Biosolids | | Agriculture, landscaping |
| | Struvite | | Agriculture |
| Phosphorus | Biosolids | 0.4–1 kg P/capita/year [10] | Agriculture |
| | Struvite: | | Agriculture |
| | Calcium phosphate | | Agriculture |
| Metals | Large variety of metals in biosolids/ash | In the order of several grams/capita/year (for the sum of all metals) | Metallurgy |
| Coagulants | Predominantly Fe and Al based | In the order of 1 kg/capita/year | Soil amendment, construction, sulfide removal and odor control |

[a] Assuming a water consumption per capita of 125 liter per day and data from [17].

(indirect potable reuse; e.g., aquifer recharge) or through the direct use of wastewater for the production of drinking water (direct potable reuse). Nevertheless, on a global scale, only a very small fraction of the municipal wastewater treated is currently being used for the production of drinking water. We would like to refer the reader to Chapter 4 of this book for a more detailed description on water reuse/reclamation and the most commonly used treatment methods.

### 1.7.2 Inerts

Depending on the size of the WWTP, sand is removed from wastewater in a dedicated treatment step to protect pumps and pipes from erosion and abrasion and reduce the amount of sludge processed in primary and secondary treatment. For example, in the Netherlands 88% of WWTPs remove sand as a separate treatment step [16]. Typical loads to a WWTP ranged between 0.1 and 3 kg capita$^{-1}$ year$^{-1}$, albeit this can be substantially higher, especially during rain events in combined sewer systems. To give an illustration of the amount of sand that can enter a WWTP, it was found that with a capacity of 250 000 PE, some 840 tons of sand per year can be recovered [16]. About two-thirds of the recovered sand was reused in the construction industry, the remainder was landfilled. It is important to realize that it is a necessity to remove the sand from an operator's perspective in order to protect equipment and as such sand recovery can be seen as a low 'hanging fruit' in terms of its resource recovery potential.

### 1.7.3 Organic matter

Considering that the organics content (measured as COD) in municipal wastewater ranges between 500 and 1200 mg COD/L (see Table 1.1), and it is estimated that some 312 million megaliter (ML) of municipal wastewater is produced annually [4], the global theoretical mass flow of recoverable organics equals to a staggering 156–374 Mton COD/year. This organic matter comprises a mixture of organic compounds, including cellulose, extracellular polymeric substances (EPS), volatile fatty acids (VFAs), proteins, lipids and (complex) carbohydrates. Starting with cellulose, this compound originates primarily from toilet paper. In the Netherlands, for example, it is estimated that toilet paper accounts for about 125–360 mg COD/L, representing 25–30% of the total COD load in WWTPs. It was estimated that with a simple sieving step, 8–10 kg cellulose per capita per year could be recovered, amounting to a recovery potential of 4.1–6.1 Mton of cellulose in the EU-27 alone [11].

Nowadays, as also mentioned above, most of the organics in municipal wastewater (e.g., VFAs, proteins, lipids or carbohydrates) are removed via activated sludge-based processes such as conventional activated sludge, nitrogen/denitrification and enhanced biological phosphorus removal (EBPR) processes. Generally, these processes separate and transform the organic matter in the wastewater, generating two organic-concentrated streams, namely primary sludge and secondary sludge. These streams contain most of the organic matter originally present in the wastewater, thus facilitating its recovery. Primary sludge generally consists of easily biodegradable particulate organics, such as carbohydrates and lipids. Secondary sludge primarily comprises less to poorly degradable materials, especially at longer sludge ages. Table 1.4 provides an overview of typical compositions of primary and secondary sludge. Note that the values listed should be seen as a guideline only as the composition can deviate depending on factors such as the local sewer catchment, industry trade waste discharge into the sewer network, type of coagulant used and presence of a sand trap.

Primary and secondary sludges are processed via dewatering/stabilization, generating a concentrated product referred to as biosolids. Biosolids can be valorized in several ways. Anaerobic digestion is a common sludge stabilization method, with the benefit of concomitant biogas generation (as discussed in detail in Chapter 5). Current biosolids disposal methods vary, being land application in agriculture, landfilling or incineration the most commonly applied. Incineration is a more common practice in Europe, USA and Asia. Land application as fertilizer or soil amendment is often regarded as the preferred strategy for beneficial reuse of organics (as well as phosphorus and nitrogen). Despite the benefits, the intrinsic properties of the sludge also come with some environmental and human health risks due to the presence of persistent organic compounds, pathogens and emerging contaminants (e.g., Per- and polyfluoroalkyl substances (PFAS). Biosolids can also be used in the cement industry, where both the calorific value of the dried sludge and the ash resulting from its incineration can be used [21]). As an example, incinerated sludge rich in iron is often used in the cement industry to produce bricks with red color.

More recently, research and development is focusing on alternative resource recovery routes by transforming WWTPs into the so-called biorefineries, to produce higher-value organic compounds

**Table 1.4** Typical composition of primary and secondary sludge, adapted from [3].

| Parameter | Primary sludge | Secondary sludge |
|---|---|---|
| Total solids (TS) (%) | 5–9 | 0.8–1.2 |
| Volatile solids (VS) (as % of TS) | 60–80 | 59–68 |
| Nitrogen (%TS) | 1.5–4 | 2.4–5.0 |
| Phosphorus (%TS) | 0.8–2.8 | 0.5–0.7 |
| Potash ($K_2O$ %TS) | 0–1 | 0.5–0.7 |
| Cellulose (%TS) | 8–15 | 7–9.7 |
| Iron (g Fe/kg) | 2–4 | – |
| Silica ($SiO_2$%) | 15–20 | – |
| pH | 5.0–8.0 | 6.5–8.0 |
| Grease and fats (%TS) | 7–35 | 5–12 |
| Protein (%TS) | 20–30 | 32–41 |
| Alkalinity (mg/L as $CaCO_3$) | 500–1500 | 580–1100 |
| Organic acids (mg/L as acetate) | 200–2000 | 1100–1700 |
| Energy content (MJ/kg TS) | 23–29 | 19–23 |

such as carboxylates, including short and medium chain fatty acids, proteins, polyhydroxyalkanoates (PHA), extracellular polymeric substances (EPS) and alginate like compounds [22–24]. Despite the increasing interest, most of these emerging concepts are still at low(er) technological readiness levels (TRL levels) and have not been applied at full-scale. One very interesting approach that has shown strong practical and economic potential that has been recently implemented at full-scale is the recovery of the alginate like compound Kaumera Nereda® Gum [25]. This polysaccharide bio-based material is extracted from the aerobic sludge granules that are formed during the Nereda® wastewater treatment process [26].

### 1.7.4 Energy from wastewater

Energy in wastewater is present as chemical energy and thermal energy. Chemical energy is present in the form of organic matter, represented as COD. The theoretical energy content of a stream can be calculated assuming an ideal conversion of COD into methane ($CH_4$) via anaerobic digestion, followed by its transformation into electrical and/or thermal energy, generally via cogeneration (combined heat and power; CHP). Under these assumptions, the typical chemical energy content of one cubic meter of municipal wastewater has been estimated at 5.5–7.0 MJ/$m^3$. The latter implies that, assuming 312 million ML is being produced globally, around 2 184 000 TJ/year can theoretically be recovered [17, 27]. Nevertheless, it must be considered that, in practice, the presence of non-degradable COD, heat losses and non-ideal conversions reduce the chemical energy recovery to around 10–14% of the theoretical chemical energy (0.6–1.0 MJ/$m^3$) [17]. Practically, anaerobic technologies are able to recover 110–3300 kJ/$m^3$ from wastewater as biogas. This implies a global potential production of 34 000–1 030 000 TJ/year of biogas from municipal wastewater, of which 52% is usually recovered as heat and 30–40% as electricity via CHP. As an example of current chemical energy recovery practices, in the EU-27, 62 383 $TJ_{biogas}$/year is produced through anaerobic digestion of wastewater sludge [28]. The energy recovered is generally used to cover the energy demands of the WWTP (around 20–45 kWh per PE in state-of-the-art plants), covering usually around half of the total energy requirements [29].

Regarding thermal energy, this corresponds to the heat energy contained in the wastewater, largely coming from bathing, laundry cleaning, cooking and the difference between the ambient and the drinking water temperature [17]. Different commercial applications for thermal energy recovery from wastewater exist, mainly based on recovery from raw wastewater. However, challenges to this approach arise due to biofouling, scaling and corrosion issues (increasing maintenance costs and reducing heat transfer capacities). Therefore, treated wastewater (with temperatures around 10–16 and 20–25°C in temperate climates during winter and summer, respectively) is nowadays considered as the best place for heat recovery [17]. Applying water source heat pumps, the net energy recovery from treated wastewater has been estimated to be around 4–8 MJ/$m^3$, depending on the environmental conditions and the utilization of the stream (e.g., heating or cooling) [17, 30]. Compared to chemical energy, these values are 4–8 times larger, underlining the potential of thermal energy recovery from wastewater. To put this into perspective, a common size WWTP (i.e., 500 000 PEs and treating 125 000 $m^3$/d), recovering both chemical and thermal energy from wastewater, could produce enough energy to cover its demands and to supply the requirements of 8800 households (at optimal conditions of 9 MJ/$m^3$ recovered and energy consumption of 1.3 MJ/$m^3$ and assuming a consumption of 29 kWh/d per household (U.S. Energy Information Administration in 2017) [17, 31]). However, when the recovered energy is to be used to displace natural gas or fuel currently used for heating, challenges like the mismatch between supply and demand cannot be ignored and would need to be addressed [24].

### 1.7.5 Nitrogen

Municipal wastewater typically contains about 30–60 mg N/L. Globally, this equals to about 20 Mton of nitrogen that ends up at WWTPs [32]. Considering that yearly 119 Mton of reactive nitrogen used as fertilizer is produced via the Haber Bosch process, this means that complete recovery of nitrogen from wastewater would equal to about 17% of all nitrogen applied in agriculture [32]. Globally, an estimated 0–15% of nitrogen from human sanitation is reused on cropland [10]. Several nitrogen recovery approaches are available and are implemented at full scale, such as struvite precipitation and ammonia stripping. However, it is important to emphasize that these approaches are restricted to side-stream and/or decentralized processes such as digestate (which only comprises about 10–25% of the total nitrogen load to a WWTP) and urine which have much higher nitrogen levels. Recovery also occurs through reuse of biosolids in agriculture, as described above in section 1.7.3. Recently, there has been an increasing interest to further upgrade the recovered nitrogen through ammonia stripping into high value microbial proteins (see Chapter 12).

### 1.7.6 Phosphorus

Yearly, in the range of 15 Mton of mineral phosphorus is mined from apatite rock and converted into fertilizer (note that also about 8 Mton of P is recycled onto agricultural land by means of manure) [33]. About 3 Mton P is ultimately consumed by humans and ends up in urine and excrements, and thus municipal wastewater. Consequentially, if all P present in municipal wastewater could be recovered, the reliance on phosphate rock can be substantially reduced by about 20%. In this context, there are three main routes currently implemented at full-scale for recovery/reuse of P at centralized WWTPs, namely: (i) P reuse in the form of biosolids, (ii) struvite precipitation and (iii) P recovery from sludge incineration ash. In conventional centralized WWTPs, P removal is achieved by means of biological P removal, chemical precipitation using iron or alum-based coagulants, or a combination thereof. Biological P removal increases the fraction of P in the secondary sludge, which leads to increased phosphate concentration in the reject water of an anaerobic digester, hence increasing the recovery potentials. Chemical P removal results in poorly degradable metal bound precipitates that end up in the biosolids. Phosphorus from incinerated biosolids can be recovered from the ash through chemical leaching processes used in the metallurgic industry [34].

### 1.7.7 Heavy metals

Heavy metals in municipal wastewater originate from a variety of anthropogenic and natural sources, which are predominantly diffuse of nature. The latter makes it virtually impossible to develop source control strategies to avoid/minimize metals ending up in municipal wastewater. A wide variety of metals are present in municipal wastewater, including Cd, Cr, Cu, Ni, Pb, and Zn [35]. These metals ultimately end up in sludge and, despite the fact that they are typically present in relatively low concentrations (i.e., mg/kg range), their presence can significantly affect the potential of (repeated) land application of sludge, as stringent regulations are in place to avoid long-term environmental problems caused by the stability and persistence of metals in nature. For example, the U.S. Environmental Protection Agency (USEPA) has specified a 'ceiling concentration' and a limited cumulative pollutant loading rate for sewage sludge application on agricultural land, whereas in the EU, The Commission of the European Communities (CEC) Directive has set both a limit to the heavy metal concentrations in sludge and a total amount of heavy metals that can be added annually to agricultural land [36].

In addition to heavy metals, it has been recently found that sludge contains a wide variety of metals, including rare-earth elements and minor metals (e.g., Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) and even platinum and gold [37], as depicted in Figure 1.3. According to the authors, the high value of some of these metals in combination with the high volume of municipal sludge could make their recovery an interesting option, with a total estimated 'metal' value of $460/ton sludge (as dry solids). In the case of sludge incineration, these metals would be concentrated in the ash. By including the ash into the feedstock of metallurgical refiners, these metals could be recovered via already employed pyro- and hydrometallurgical processes. It should be noted that due to the complex mixture of a wide variety of metals in combination with their very low concentrations (Figure 1.3), their recovery remains highly challenging from a technical and economic perspective. Note that the concentrations presented in Figure 3 can differ depending on the geographical location and catchment characteristics.

### 1.7.8 Coagulants

Aluminum and iron-based coagulants are commonly used in wastewater systems for phosphorus and/or sulfide removal. To illustrate the reliance of urban water management on chemical dosage, according to a recent market analysis, the global chemical market for the water industry was estimated to be 6 billion USD, with a further estimate increase to about 8.5 billion USD by the year 2023 [38]. Iron salts (mostly ferrous and/or ferric chloride) are often dosed to sewer networks to combat hydrogen sulfide induced corrosion of concrete sewer pipes, a notorious and costly problem for wastewater utilities

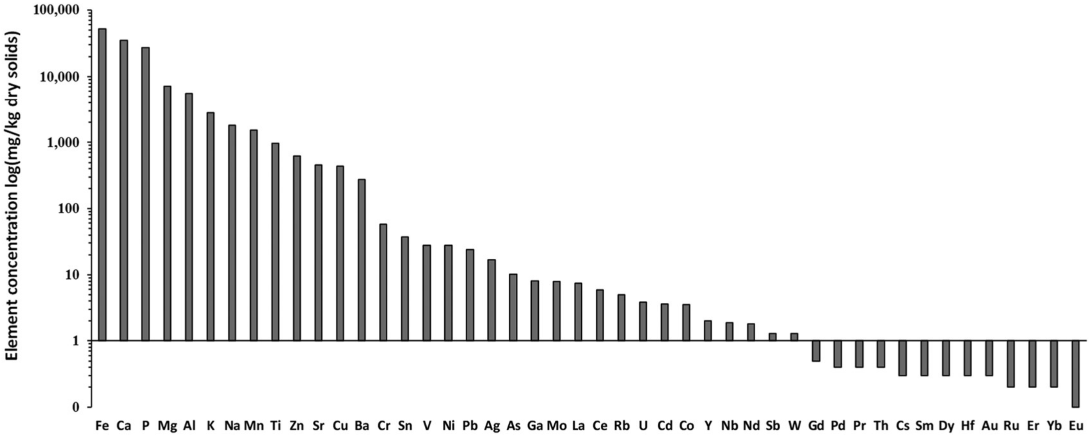

**Figure 1.3** Example of the wide variety of metals (and other elements) that can be present in sludge. The figure shows data of sludge from a WWTP in arizona, as described in detail elsewhere [36].

worldwide [39]. Most WWTP still rely heavily on the addition of either iron (Fe) or aluminum (Al) based salts (mainly $FeCl_2$ or $FeCl_3$ and $Al_2(SO_4)_3$) for chemical phosphate removal. Lastly, iron salts are often dosed to anaerobic digesters for sulfide control. It is expected that these chemicals will keep playing an important role in the coming decades. This makes their recovery interesting. Typical dosing concentrations are in the order of 5–50 mg/L Fe or Al based coagulants, respectively. Depending on the dosing rate and WWTP configuration, Fe and Al contents in the sludge are typically in the order of $\sim$0–50 g/kg dry solids.

## 1.8 CHAPTER SUMMARY

Municipal wastewater can be defined as a waste stream consisting of a mixture of human excrements from toilet use and water originating from household activities such as cleaning, washing and cooking. In this chapter, the typical production rates and composition of the various streams (i.e., yellow, grey and black water) comprising municipal wastewater and how they are typically collected has been discussed. Moreover, the chapter describes how much municipal wastewater is generated per capita and, globally, how this wastewater is typically collected and treated. The key resources that are present (or added during the treatment process) in municipal wastewater that potentially can be recovered during its treatment have also been outlined. Moreover, the typical concentrations ranges at which these different resources are present, as well as in what form these resources can be recovered, have been discussed. After reading this chapter, the reader should have gained an appreciation of the order of magnitude of municipal wastewater generation and the concentration and mass flows of the plethora of resources embedded in municipal wastewater. In this context, the importance of centralized systems for treating municipal wastewater on the potential for resource recovery in terms of economy of scale should not be ignored. Many resources can potentially be recovered from municipal wastewater, depending on the technology implemented. However, it is evident that there is no 'one size fits all' combination of technologies/configurations that allows to recover each and every resource present in the wastewater and choices need to be made which product to prioritize. Finally, one should never forget that with >99% of the total mass flow, the major recoverable resource in municipal wastewater is water. All other resources are present in diluted form at relatively low concentrations.

## 1.9 EXERCISES

**Exercise 1.1:** A wastewater treatment plant services a community of 50 000 people residing in a catchment of 30 km$^2$. Assume that 90% of the inhabitants are connected to the combined sewer network and that 10% of the people are living too remotely to be connected to the centralized sewer network and have household based septic tanks. In order to improve the sustainability of urban wastewater management of the community, resource recovery of nitrogen (in the form of ammonium) has been raised as a potential priority by the city council. In this context, recent developments aimed to recover nitrogen from urine (urine has a high N content, see Table 1.1) have gained special interest in recent years. Let us assume that indeed ammonium recovery from urine at a household level can be achieved, and based on this assumption, calculate the following:

(a) Calculate the amount of nitrogen that can be recovered on a daily and annual basis per household (assuming an average of four people per household) and an N recovery efficiency of 90%.
(b) Calculate the amount of nitrogen that can be recovered at the WWTP assuming a recovery potential of 25% of the incoming N load at the WWTP.
(c) Considering the values found in (a) and (b), describe the practical limitations of resource recovery at a household level.

(d) In addition to the practical issues raised in (c), it is important to realize that ammonium is considered a bulk product produced at low cost and at very large industrial scale through the Haber–Bosch process. Explain why this could further reduce the economic potential of decentralized N recovery.

**Exercise 1.2:** A community in Indonesia must build a centralized wastewater treatment system. The system is to service the 60 000 people of the district. An anaerobic pond is selected as a low-cost treatment system in order to treat the water to achieve a safe discharge level of $BOD_5$ of 50 mg/L and capture the biogas for powering gas burning stoves in the community, or burning it to provide a local and renewable source of power for the community. The typical per capita wastewater characteristics highlighted in Table 1.1 apply.

(a) Estimate the following influent parameters for the sewage stream (mg/L): $BOD_5$, COD, TN, TP.
(b) Calculate how much methane ($m^3$/d and GJ/d) could be recovered from the anaerobic pond (assume 0.18 $m^3_{\text{methane produced}}/\text{kgBOD5}_{\text{removed}}$ and that the energy content of methane is approximately 37 MJ/$m^3$) and determine the number of households that would be supported through the use of this gas for the case of:
    (i) Cooking gas: where an average household of 5–6 uses 70 MJ/d of methane to power their cooking stoves, or
    (ii) Electricity: assume the energy conversion from methane to electricity is 0.3 and a typical family uses 10 kWh of electricity per day (1 kWh = 3.6 MJ). Comment on the advantages/disadvantages of each proposed plan for methane recovery.

**Exercise 1.3:** The Canadian city of Halifax is building an activated sludge system at its main wastewater treatment plant that services 170 000 people. Two resource recovery strategies are considered for the sludge produced from this treatment facility, the first consists of one-stage anaerobic digestion for methane recovery from biogas and the other is polyhydroxyalkanoate (PHA) recovery through a 3-stage process. The 3-stage PHA process consists of: (1) anaerobic sludge fermentation to volatile fatty acids (VFA), (2) aerobic culture selection through a feast/famine process fed with the effluent of (1), and (3) PHA accumulation from the selected culture in (2) using the effluent of (1). Assume standard (i.e., Table 1.1) wastewater flows and characteristics and that 80 gVSS of sludge are produced per $m^3$ of wastewater treated by the facility. Considering that the value of PHA is \$3.5/kg and that the value of methane is \$0.4/$m^3$, where 1 $m^3$ of biogas (with a methane content of 65%) is produced per kg of VSS, while 0.1 kg of PHA are produced per kg of VSS in the 3-stage process:

(a) Determine the relative value of the sludge stream using either the PHA recovery or biogas recovery strategy
(b) Discuss the key factors impacting the capital and operational expenditures associated with biogas or PHA production. Which process is likely to incur higher production costs? Why? What would you consider to be the key points impacting your decision on the process to be implemented?

**Exercise 1.4:** A utility is required to establish wastewater treatment strategies for remote communities at the household level (average of four inhabitants per household) and is considering source separation of the urine from the influent wastewater for nitrogen recovery as a fertilizer to be applied agriculturally. Considering the N loading per capita of Table 1.1 and that the N load per hectare required for fertilization is 14 kg N/ha, how many households would be required to meet the fertilizer demand for 12 ha in 30 days?

**Exercise 1.5:** An apartment building in Beijing houses approximately 2500 inhabitants, where source separation of urine is considered to be implemented for both nitrogen and phosphorus recovery that will be transported to a neighboring region for fertilization purposes. Consider that the N and P loading per capita of Table 1.1 applies and that the N and P loads per hectare required for fertilization are 21 kg N/ha and 9 kg P/ha, respectively. How many hectares could be fertilized from this building per year? What would be the limiting nutrient?

**Exercise 1.6:** A music festival in Lisbon will have approximately 12 000 people in attendance during the event. The water utility of the region plans to institute source separation of urine from the wastewater at the event to provide a fertilizer for a nearby agricultural region where nitrogen is the limiting nutrient. Considering the N loading per capita of Table 1.1 and that the N load per hectare required for fertilization is 18 kg N/ha, how many hectares could be fertilized per day?

**Exercise 1.7:** The Singapore airport services approximately 227 000 passengers per day, where source separation of urine will be implemented for both nitrogen and phosphorus recovery for fertilization. Considering the N and P loading per capita of Table 1.1 and that the N and P loads per hectare required for fertilization are 31 kg N/ha and 2.5 kg P/ha, respectively, how many hectares could be fertilized from the airport per day? Will N or P be the limiting nutrient?

**Exercise 1.8:** Titanium dioxide nanoparticles are increasingly used in a variety of commercial products such as textiles, paints and personal care products, and the fate of a great part of this titanium is wastewater. Indeed, up to 4% of the $TiO_2$ applied onto textiles can wash off in a single wash [40], and they are part of numerous daily life products such as sunscreen and toothpaste, resulting in relevant concentrations of $TiO_2$ nanoparticles being washed into municipal wastewater systems (Figure 1.3). $TiO_2$ must be removed in WWTP since it has been demonstrated that, if left untreated, it can be harmful to aquatic life. Up to 85% of titanium typically ends up in the biosolids due to the low solubility of $TiO_2$. The state of Arizona conducted a feasibility study regarding viability of recovering $TiO_2$ in WWTP. It was found that the titanium concentrations in raw wastewater ranged from 181 to 1233 μg/L (median of 26 samples was 321 μg/L) [41]. Consider for this study the WWTP of Phoenix 91st Avenue, which serves a population of 2.5 million people, treating a flow rate of approximately 870 ML/day. Two processes of $TiO_2$ recovery are proposed, one from liquid influent, and another from the biosolids, which are produced at a rate of 100 kg DW/ML of influent wastewater treated. Estimate the minimum concentration of $TiO_2$ in the influent or in the biosolids to make recovery economically viable for either scenario, assuming recovery efficiencies of 95 and 90% for the liquid effluent and the biosolids, respectively. Assume process costs of $30/ML of influent wastewater and $58/tonDW of sludge produced, and a value of $TiO_2$ of $60 per kg.

**Exercise 1.9:** Given that a small town with 3000 inhabitants is interested in investing in the implementation of an anaerobic digester at their centralized WWTP:

(a) Calculate the practical calorific biogas production potential of the small town using the data provided in Table 1.3.
(b) In (a) you have calculated the potential biogas production. How does this compare to natural gas given that the annual per capita natural gas consumption equals to 2361 $Nm^3$ (average consumption in the US? Assume that 1 $Nm^3$ of natural gas has a caloric value of 40 $MJ/m^3$.

**Exercise 1.10:** In this chapter, the different waste streams comprising municipal wastewater have been discussed, without the help of the information provided in this chapter, fill in the table below.

| | Grey water (%) | Urine (%) | Feces (%) |
|---|---|---|---|
| Flow rate | | | |
| COD | | | |
| Nitrogen | | | |
| Phosphorus | | | |
| Potassium | | | |

**Exercise 1.11:** Considering (i) the metal concentrations depicted in Figure 1.3, (ii) typical coagulant dosing rates in the form of either alum or iron-based coagulants and (iii) sludge production rates of 8 000 000 and 9 253 000 ton DM sludge/year for the US and EU, respectively, estimate the total mass flows by filling in the table below.

| Metal | Concentration in sludge (mg/kg dry weight) | Total estimated amount in the EU (ton/year) | Total estimated amount in the USA (ton/year) |
|---|---|---|---|
| Fe | | | |
| Al | | | |
| Ti | | | |
| Zn | | | |
| Cu | | | |
| Ag | | | |
| Yt | | | |
| Nd | | | |
| Au | | | |
| Pd | | | |

## 1.10 DISCUSSION QUESTIONS

**Question 1.1** (technology and economy): As the innovation manager of a large water utility, you are in charge of reorganizing the existing water infrastructure from its current situation to a more circular approach within a timeframe of 15 years. The current wastewater treatment infrastructure comprises two very large-scale wastewater treatment plants, with a capacity of 400 000 and 500 000 PE, both using conventional activated sludge plants of 400 000 and 350 000 PE. In addition, it comprises more than 50 small size WWTPs with a capacity between 500 and 1500 PE. You are asked to give a presentation to the board of directors in which you evaluate the current status and justify your masterplan. Where would you focus on in terms chosen technology, location (i.e., which WWTP to focus on) and which resources would you target? What are your key considerations/motivations?

**Question 1.2** (drivers and market analysis): A wastewater utility operating a WWTP with a capacity of 500 000 PE is evaluating the feasibility of upgrading their treatment processes using advanced treatment processes in order to generate an effluent that exceed drinking water quality. As the business development manager of the wastewater utility, you are asked to give a presentation to the board of directors in which you evaluate the economic potential, technical constraints as well as social implications/considerations that need to be taken into account. What are the key criteria and considerations that should be considered?

**Question 1.3** (drivers, risks and social acceptance): As discussed in this chapter, the ultimate disposal (or reuse) route of biosolids differs amongst the different regions in the world with beneficial reuse in agricultural application, landfill and incineration the most commonly applied approaches. Evaluate these three options and provide a list of potential advantages and disadvantages for each of these options.

**Question 1.4** (drivers, targets, policy and sustainability): With an ever-growing population and increasing living standards, the world needs increasing amounts of inorganic fertilizer. Important ingredients of fertilizer include ammonium and phosphorus. Ammonium is produced in large amounts (i.e., over 100 million tons per year) via the energy-intensive Haber–Bosch process. The process involves the reaction of $N_2$ (which comprise 80% of our atmosphere!) with hydrogen under high temperature and pressure in the presence of an iron catalyst. Phosphorus on the other hand, is a non-renewable resource that is mostly extracted from mineral phosphorus-rock deposits. An important aspect is that only a few countries have significant deposits, with Morocco, China, Algeria and Syria being the top four. Considering the above-described information, discuss the necessity and key drivers for nitrogen and phosphorus recovery and also evaluate the potential environmental benefits and social impact.

**Question 1.5** (market analysis, risks and economy-of-scale): In developed countries, the wastewater infrastructure is ageing and would require major upgrades in the coming decades. In less developed countries and emerging economies a significant amount of new infrastructure will need to be realized in the coming decades. Considering the above, there is an ongoing debate regarding how our future urban waster infrastructure will look, that is, more centralized or more modular and decentralized. Evaluate the general characteristics of centralized and decentralized systems and provide advantages and disadvantages for each of these scenarios in the context of resource recovery, taking into account economy of scale, practical feasibility and maintenance, monitoring and quality control and market requirements of recovered resources.

**Question 1.6** (rare earth metals, economics): As depicted in Figure 1.3, a wide variety of elements can be found in sludge. In fact, even gold and platinum can be found in sludge. Due to the high value of gold and platinum and other elements, it was estimated that when adding up the values based on the individual prices of these elements, sludge can be valued at $460/ton sludge. Some people argue this is a too simplistic economic assessment. Discuss potential economic and technical challenges that would substantially reduce the overall process economics of recovery of high-value elements from sludge.

**Question 1.7** (rare earth metals, environmental impact): In the questions above, you have highlighted several economic and technical challenges with respect to recovery of high value elements from sludge. Let us assume a situation where all economic and technical constraints have been solved for the situation where the sludge is incinerated and the metals can be recovered from the sludge ash. Even in this scenario one could provide arguments as to why other approaches such as beneficial land use as a fertilizer would be better. Examine the various sludge management strategies and discuss what could be considered important aspects/drivers that would need to be assessed in detail.

**Question 1.8** (design considerations, process stability, down-stream processing): Various approaches aim to produce and recovery high-value products as a means to improve the overall economics of resource recovery from wastewater. In this context, a very interesting approach is Kaumera Nereda® Gum. Interestingly, and an important aspect to consider, is that the Nereda® technology was not specifically developed and designed with the purpose to recover Kaumera. In fact, the primary objective was to reduce the costs of municipal wastewater treatment and the observation that the polysaccharide bio-based material Kaumera could be recovered from excess aerobic granular sludge in a completely independent side-stream process was made at a later stage. Discuss the potential benefits Kaumera may have from a process stability/robustness and wastewater operator confidence and willingness to introduce this recovery method in relation to other resource recovery methods such as struvite precipitation and ammonia stripping.

**Question 1.9** (economic considerations, market demands, decision-making): For exercises 1.4–1.7, comment on the potential for N and P recovery and the process challenges that would be encountered in each case. Comment on the impact of economies of scale on the economic and practical potential of recovery of N and P through source separation.

**Question 1.10** (economic considerations, market demands, decision-making): You are the Innovation Manager of a large wastewater utility that needs to prioritize the resources to be recovered from your largest wastewater treatment facilities. Not all resources that are of potential interest can be recovered simultaneously, while the recovery of some components may impact your capacity to recover other components. Outline your top five resource priorities to be recovered and justify well each of your choices.

**Question 1.11** (integrated management, multiple reuse, asset management): Sewer networks are million-dollar assets that are exposed to severe corrosion problems arising from sulfate present in wastewater. Large amounts of iron salts are continuously applied to precipitate sulfate thereby reducing the hydrogen sulfide generated in sewers in order to control corrosion and odor. Knowing that coagulants are also used in drinking water treatment systems and for the removal of phosphorus in WWTP, discuss an integrated approach for water management in a perspective of achieving multiple objectives from a single coagulant application. What possible obstacles could arise is reusing iron salts within the urban water cycle?

**Question 1.12** (design considerations, enhanced energy generation, unwanted side-effects) In various cities around the world, the idea has been proposed to use the existing underground sewer network to transport other waste rather than just sewage. In fact, in several parts of the world the installation of grinders in kitchen sinks are a common way to deal with organic kitchen waste. For example, according to the USA Census Bureau (2011), almost half of the kitchens in the US were equipped with these grinders. As organic kitchen waste increases the degradable organic load in the sewage that could be recovered as biogas during anaerobic digestion, one could see the synergy – reducing the amount of solid waste landfilled coupled with enhanced biogas production. While principally this holds true, the approach also comes with important disadvantages that need to be considered such as unwanted methane formation in the sewer network itself. Discuss whether the increased methane production outweighs the disadvantages and risks.

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