Chapter 6

Urine source separation for global nutrient management

Abstract In the global perspective, the sewer-based paradigm for wastewater management is not successful neither from a humanitarian nor from an environmental perspective. The system is too expensive for the largest part of the global population. Source separation and resource recovery offer an alternative for sanitation and water pollution control. This chapter illustrates the importance, but also the challenges of urine source separation for efficient nutrient removal and recovery.

Keywords disruptive innovation, environment, sustainable, technical, toilets, wastewater treatment plants

1 Introduction

Urine source separation for nutrient recovery can be compared to the well-known source separation for solid waste, but was only adopted by the scientific community since the 1990s (Hanæus et al. 1997, Hellström and Kärrman 1997, Henze 1997, Jönsson et al. 1997, Larsen and Gujer 1997, 1996).

Urine separation would be a disruptive innovation in the entire system of urban wastewater management, leading to larger investments at the household level, but smaller investments in municipal infrastructure. This chapter argues that the innovation is not only beneficial, but may also be essential in order to achieve sufficient nutrient removal from wastewater in most areas of the world. It also explores some of the challenges as well as the technical opportunities for introducing such a radical change to the urban water cycle and gives a few examples of urine separation as an addition to rural wastewater treatment.

1.1 Why urine source separation?

Urine contains the majority of the water-relevant nutrients nitrogen (N) and phosphorus (P) excreted from human metabolism: nearly 90 % of N and nearly 60 % of P, as well as large amounts of potassium (K) (Larsen and Gujer 1996). With a present world population of 7.5 billion, these nutrient contributions amount to roughly 25 Mt/year of nitrogen, 1.8 Mt/year of phosphorus and 5.5 Mt/year of potassium. These nutrients have a value, if recovered, of more than 20 billion US\$ on the global market, even at the relatively low fertilizer prices experienced in 2014 (World Bank 2015) and for the production of this amount of ammonia for agricultural use, about 1100 PWh/year of primary energy are required (Maurer et al. 2003). Further it should be noted that local fertilizer prices may be up to a factor of 2-3 higher than global market prices, especially in land-locked countries with poor supply networks (Gregory and Bumb 2006).

Fertilizer costs are high, but they are dwarfed by the potential costs of protecting the environment from the nutrients through sewer-based wastewater treatment. Nutrient elimination is part of urban water management in order to protect surface water against eutrophication. In industrial countries, the costs of nutrient elimination are estimated at 20-40 US\$/cap/year (Maurer et al. 2005). If we would equip the present global population of 7.5 billion with this nutrient removal technology as an addition to basic wastewater treatment plants, the total costs would be 150-300 billion US\$/year – about 10 times higher than the market value of the nutrients.

In reality, the costs will be much higher. The estimated costs of nutrient elimination cited above imply that sewers and basic treatment plants (without nutrient elimination) are already available. For the 70 % of the world population, which is presently not connected to any sewer system (Van Drecht et al. 2009), the global costs would be about seven times higher to establish collection systems and basic treatment plants (Maurer et al. 2005). The total global costs of introducing conventional nutrient elimination for the entire global population would thus be in the order of size of a trillion US\$/year. The advantage of urine separation technology is that a large part of the huge amount of nutrients in urine can be collected without any initial investments in a sewer system.

Existing biological treatment plants would not require any upgrading to advanced nutrient removal if urine separation is implemented. Without N and P from urine, domestic wastewater would have a balanced C:N:P ratio, meaning that a simple biological wastewater treatment plant with a short sludge retention time (SRT) could reach excellent N and P emission standards (Larsen and Gujer 1996). In a modeling study for a specific catchment, Wilsenach and van Loosdrecht (2006) showed that with biological aerobic treatment at an SRT of 0.8 day (as

compared to at least 12 days for a plant removing nutrients), the process would become N-limited at 90 % urine separation. The effluent P concentration would be around 1 gm^{-3} , which is a typical effluent requirement, but it would only take a very small amount of precipitant to reduce this value further if needed for sensitive aquatic environments. Since the tank size of the biological unit of a wastewater treatment plant is proportional to SRT, such a plant could be much smaller and cheaper.

1.2 Challenges

There are good reasons to introduce urine source separation as part of mainstream wastewater management. There are, however, a number of reasons why urine separation is still only implemented in simple settings, primarily in rural settings of low-income countries. At present, there is neither technology nor institutions for introducing wide-spread urine source separation in an urban environment. Furthermore, transport of urine is difficult, calling for decentralized or even on-site technologies, which are traditionally not in the repertoire of wastewater management authorities. Technologies, including small-scale, for urine treatment are in development and so are urine separating flush toilets (NoMix toilets). The most difficult hurdle may be the attitude of stakeholders and decision-makers: Why change a successful system like advanced nutrient removal when it is not absolutely necessary? In order to understand why this may still be rewarding, this chapter will start with a review of the problems and challenges of conventional advanced nutrient removal.

2 Why will conventional advanced nutrient elimination not contribute much to solving the problems of aquatic ecosystems on a global scale?

Advanced nutrient elimination at treatment plants is a powerful technology, which has allowed maintaining or recovering the quality of aquatic ecosystems in many countries. However, in even more countries, it has not been possible to introduce this technology although it has been available for nearly half a century. Additionally, there are other disadvantages, which could be mitigated with innovative technology: issues of energy consumption and climate change.

2.1 The role of wastewater nutrients for eutrophication of aquatic ecosystems

The role of nitrogen and phosphorus for eutrophication of aquatic ecosystems is well-established. As a general rule

of thumb, phosphorus causes eutrophication in lakes, and nitrogen causes eutrophication in coastal areas (Howarth and Marino 2006). Normally, agriculture is considered the main source of N and P, but urban areas are also contributing significantly to nutrient loads (Withers et al. 2014). The important role of larger cities in hypoxia has been shown, e.g. by Lajaunie-Salla et al. (2017), and as argued by McCrackin et al. (2017), even where the emissions are dominated by agriculture, a combined effort including nutrient removal at treatment plants are often required to solve the problem. Effective nutrient removal from wastewater is thus a very powerful tool for improving the quality of aquatic ecosystems in the vicinity of cities.

2.2 Advanced nutrient elimination on a global scale

Globally, wastewater treatment plants remove only 20 % of P and 10 % of N contained in wastewater (Figure 1). The reason is that low and middle income countries have not invested in nutrient-eliminating wastewater treatment plants (Van Puijenbroek et al. 2015). The same figure projects that the amounts of N and P emitted to the environment will increase in the future: it is not possible to construct infrastructure rapidly enough to cope with the increased nutrient emissions of a growing world population.

Figure 1 Total nutrient input (N and P) to wastewater on a global scale.

Most of the nutrients are and will be emitted from people who are not connected to wastewater treatment plants. Where people are connected, removal rate is increasing, but population growth and better nutrition are expected to outweigh this improvement. Data and model predictions are compiled from Bouwman et al. (2009), Van Drecht et al. (2009). Model predictions for 2030 and 2050 are average values from four generally accepted socio-economic models for the future.

2.3 Climate relevance of wastewater nitrogen transformation

Nitrogen transformation is climate-relevant in several ways at wastewater treatment plants: nitrous oxide (an important climate gas) is emitted from nitrifying treatment plants, energy is consumed in the nitrification process, and production of energy-rich sludge is reduced due to the long solid retention time (SRT) required for conventional nitrogen transformations. Nitrogen removal (transformation to N_2) also means a loss of chemical energy embedded in reactive nitrogen through nitrogen fixation (transformation of N_2 to ammonia, either biologically or chemically). It can be shown that nitrogen recovery from urine holds the highest potential for climate-friendly wastewater management, especially if N_2O emissions can be avoided, e.g. if recovery would take place without ammonia oxidation (Larsen 2015).

3 Nutrient Recovery

Steffen et al. (2015) identified the major areas of global environmental risk, using the notion of “planetary boundaries”. The idea is that within these boundaries, the risk of destabilizing the Earth is low. According to the

authors, the emission of N and P already surpasses the corresponding “safe” boundary, primarily due to eutrophication of the oceans on a global scale. In earlier similar work, Rockstrom et al. (2009) pleaded for a strongly reduced production of reactive nitrogen (all nitrogen species except N_2), in order to keep the amount of reactive nitrogen within the boundaries identified as “safe”. At the same time, large amounts of nitrogen are essential to feed a growing population, and nitrogen recovery from wastewater is thus a logical path to follow.

3.1 Nutrient recycling from conventional wastewater treatment plants

The most direct way of recovering nutrients from wastewater is direct use of wastewater for irrigation. This technology was used historically, e.g. in Paris from 1872, but already from the beginning, the high demand for space made it impossible to treat the entire wastewater from Paris (Védry et al. 2001). The technology is still in use at places where enough agricultural land is available and where consumers tolerate the risk of anthropogenic contamination.

All types of phosphorus removal on treatment plants transfer phosphorus to the sludge fraction. Sludge is frequently spread to agricultural land, primarily to save costs for sludge disposal, but also in order to recycle phosphorus.

Depending on the processing technology, phosphorus from sludge may be bioavailable (Kahiluoto et al. 2015), but in some European countries, consumers are opposed to the use of sewage sludge on agricultural land due to the fear of inorganic, organic and infectious contamination. In Switzerland, this fear resulted in a legal ban of wastewater application (Lienert and Larsen 2007), whereas in Sweden, the use was strongly reduced because the large food retailers do not accept food produced in areas fertilized with sewage sludge (Bengtsson and Tillman 2004).

About 20 % of wastewater nitrogen can be recovered from digester supernatant through stripping (Boehler et al. 2015), but this technology has not yet been broadly implemented. Within the existing system, it is difficult to recover more than these 20 %. In principle, ion exchange with zeolites (Sutton et al. 2011, Wang et al. 2014) as well as adsorption on activated carbon (Czerwionka and Makinia 2014) from wastewater are possible, but this is not efficient. More experience is available for the uptake of nitrogen in biomass from municipal wastewater. Effective uptake of N can be achieved with water hyacinths or duckweed (Zhao et al. 2014), but for uptake with less space requirements, algal ponds are considered more suitable. However, even for High Rate Algal Ponds (HRAP), space demand will be around 10 m²/person (based on loading information in Craggs et al. (2012)), resulting in a large space requirement of 50 ha for a medium-size town of 50'000 inhabitants, which is unlikely to be implemented.

The difficulties of recovering nitrogen from diluted wastewater is one of the most important reasons for discussing nutrient recovery from toilet waste. With urine containing around 90 % of the nitrogen from the human metabolism, urine separation is the most obvious technology for efficient nitrogen recovery.

Direct use of urine or even combined toilet waste are traditional technologies (Bracken et al. 2007), which obviously have a large potential to recycle nutrients from the human metabolism. New sanitization methods have been developed and tested: e.g. prolonged storage for urine (Hoglund et al. 2002) and urea treatment for combined toilet waste, aka blackwater (Fidjeland et al. 2015). As shown by a number of Life Cycle Assessment (LCA) studies, direct recycling of urine and blackwater is highly beneficial from an environmental point of view, as long as ammonia emissions are kept to a minimum (through proper storage and spreading technologies) and transport distances to agricultural land are not excessive (see e.g. Tidåker et al. (2007)). For urban areas, transport of urine to agriculture is not practical, and processing of the urine is therefore necessary.

4 Urine separation in an urban environment

Recovery of nutrients from urine in urban settings places high demands on technology. Maurer et al. (2006) states that the process engineering goals are primarily volume reduction, stabilization, sanitization, and removal of micropollutants. Volume is certainly the most important issue for transfer of urine from urban areas to agriculture. Ledezma et al. (2015) report findings that in Australia, the transport of urine from urban areas to agriculture would be more expensive than the costs of the equivalent fertilizers. The volume of urine, at 1.5 L/person/day, is in the same order of magnitude as domestic solid waste. Collection in a city would thus mean doubling the transport requirements for domestic waste – a huge effort with large financial consequences. Stabilization with respect to odor and ammonia emissions is equally important: weekly collection of un-stabilized urine in an urban environment would probably be possible, but at a high price. Sanitization is necessary mainly due to cross-contamination with fecal pathogens (Hoglund et al. 2002). Finally, micropollutants in urine are important: about two thirds of the pharmaceuticals excreted from the human metabolism are contained in urine (Lienert et al. 2007a). As shown by Bischof et al. (2015), high concentrations of pharmaceuticals may be found in urine from areas with a high prevalence of HIV. Although those are the more polar (water-soluble) ones and therefore less critical than the lipid-soluble ones contained in feces, urine still contains half of the ecotoxicologic potential from human excretions (Lienert et al. 2007b).

4.1 Technical options for nutrient recovery from urine

Urine is essentially a highly concentrated nutrient solution with a few annoying properties (Udert et al. 2006). The main problems are odor and a high pH value, which causes a high concentration of gaseous ammonia and thus can lead to large nitrogen emissions during transport and handling of urine. For more than 10 years, a small number of researchers have developed different biological, physical-chemical, and electrochemical approaches in order to reduce the volume, stabilize the solution (i.e. reduce odor and pH), and eventually produce a hygienic fertilizer, possibly without micropollutants. Maurer et al. (2006) documented the first attempts, and in the meantime, many other technologies are under development. One of the technologies, which have gone the furthest, is the stabilization of ammonia by partial nitrification (decreasing the pH-value and thus pushing the equilibrium towards non-volatile ammonium) followed by distillation for volume reduction (Fumasoli et al. 2016).

The choice of urine treatment technology will depend on a large number of local factors, which will not be discussed here. McConville et al. (2014) presents a suitable methodologies for system designs.

4.2 Acceptance of urine source separation

A common criticism of urine source separation concerns public acceptance. Many people anticipate that users will not accept NoMix toilets and that farmers will not want to use a urine-based fertilizer. Whereas it is true that users are critical towards NoMix toilets (shown in Figure 2), especially when they have them at home, this has more to do with the toilet technology on the market than with a general lack of acceptance. In a review, Lienert and Larsen (2010) found that in Europe about 80 % of people who have experienced the present NoMix toilets are in favor of the technology despite the daily problems with the toilets. People living with the toilets at home tend to be more critical than those experiencing NoMix toilets only at the work place. Consumers as well as farmers (Pahl-Wostl et al. 2003) would also accept a urine-based fertilizer if they could be convinced that this fertilizer would be safe: safety being associated with hygiene and the absence of pharmaceuticals from the human metabolism.

Figure 2 The NoMix toilet, which has been in use at Eawag since 2006. Urine is collected at the front; the rest of the toilet functions as any conventional toilet. A special mechanism ensures that only little flush water finds its way into the urine tank © Eawag.

In areas where urine diverting dry toilets (UDDTs) are applied, satisfaction with existing toilet technology is poor. In the municipality of eThekweni, South Africa, Roma et al. (2013) found a very low satisfaction with the toilets after 10 years of implementation. New and better technology are needed for UDDT acceptance.

5 Future Research and Implementation Projects

Researchers and some practitioners have been discussing urine separation for about 20 years, but still there are very few full-scale implementations. Although a period of 20 years is not a long development time for a highly disruptive technology like urine source separation, it is valuable to reflect on the obstacles and the way forward.

There are many places where urine separation would make sense and where one could develop good transition scenarios. Three of those situations will be discussed here.

In growing cities, urine separation could avoid expensive extensions of wastewater treatment plants (Borsuk et al. 2008), a solution which has also been investigated in a master study at the water utility SIAAP in Paris (Caby 2013). Paris will grow by 10 % over the next 10 years and the treatment plants have no capacity to cope with the extra

nitrogen. The introduction of targets for nitrogen emissions in cities that previously had none results in the same situation, as exemplified by the city of Hong-Kong. In this city, onsite nitrification of urine followed by denitrification in the sewers has been considered as an alternative to the upgrading of existing treatment plants to nitrifying-denitrifying plants (Jiang et al. 2011).

Another possible transition scenario is on-site wastewater treatment in rural areas of high-income countries, which may help mature the technology for later urban implementation. Wood et al. (2015) have shown that urine separation would be a low-cost, very effective add-on to existing septic tanks. In a similar situation, urine source separation is already implemented in Sweden as a powerful technology for preventing nutrient pollution from rural areas where only simple wastewater treatment is available (Vinnerås and Jönsson 2013).

The third possible situation is again found in Hong-Kong, where seawater is used for toilet flushing due to water scarcity. Seawater provides high sulfate concentrations in the sewers and anaerobic conditions therefore lead to sulfide production causing corrosion (Ekama et al. 2011). Onsite nitrification followed by denitrification in the sewers would not only solve the problem of treatment plants as discussed above, but also prevent sulfide production in the sewers. This is due to the preference of microorganisms for nitrate over sulfate as an electron acceptor, producing inert N_2 gas instead of hydrogen sulfide. Hong-Kong foresees recovery of phosphorus as struvite (magnesium ammonium phosphate) with sea water as its magnesium source, followed by on-site full nitrification followed by in-sewer denitrification (Mackey et al. 2014).

Today, full-scale urine separation is primarily implemented in rural areas of low-income countries where it makes dry toilets less smelly and reduces logistic costs because urine is considered less of a hygienic risk and is, therefore, just infiltrated. The largest implementation of this type of urine separation is the eThekweni water utility in Durban, South Africa, where more than 75'000 urine-separating dry toilets were in use in 2013 (Udert et al. 2015). A large research project, financed by the Bill & Melinda Gates Foundation (www.eawag.ch/vuna), investigated the possibility of introducing collection of urine followed by nutrient recovery. The reason for urine collection is, on one hand, the protection of drinking water resources and, on the other hand, the fertilizer production from urine.

The largest hurdle for further developments of urine source separation in low-income as well as in high-income countries is the lack of good urine separating toilets, be it in the dry variation as UDDTs or in the flushed variant as NoMix toilets. In low-income countries, cheap urine-separating solutions already exist, but the aspiration of low-

income users are for flush toilets, not for better UDDTs (Roma et al. 2013). It has been shown that these hurdles can be overcome by combining UDDTs with a separate water cycle (Kuenzle et al. 2015, Larsen et al. 2015): it will be necessary to bring the costs of those improved UDDTs down to a level where they are economically attractive for the target population. For high-income countries, the design demands from consumers for NoMix-type toilets are requiring ceramic producers to develop fundamentally new toilets. Existing wastewater infrastructure is able to upgrade wastewater treatment plants to nutrient elimination, which reduces the adoption rate of urine-separation. Middle-income countries have little pre-existing wastewater infrastructure and are positioned as the most interesting part of the world for practical development of urine source-separating technology.

Urine source separation is a developing research and implementation area. On a global scale, there seems to be few alternatives to recover nutrients and protect surface water against eutrophication. A large portfolio of promising technologies have been developed, but only partial nitrification followed by distillation is close to technical maturity, a technology that can be implemented at the scale of a multi storage building. Newer chemical and bioelectrochemical technologies hold high promises for smaller-scale applications with the hope of developing small, bathroom-sized applications within the next decade.

6 References

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