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SUSTAINABLE WASTEWATER TREATMENT SOLUTIONS FOR WATER-SMART CIRCULAR ECONOMY

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Abstract

The Protection of aquatic water bodies and human health is a paramount objective accomplished by wastewater treatment systems. Traditionally, pollutants are managed and removed in wastewater treatment plants (WWTPs), following a paradigm in which wastewater is considered a waste. Wastewater treatment requires significant amounts of resources, such as energy and chemicals, while sludge is produced, requiring further treatment.

A decade ago, a new paradigm emerged, suggesting that municipal wastewater is a source of resources, particularly reclaimed water, materials (e.g., nutrients) and energy. Many processes applicable for this new paradigm already existed, and others have been further developed (struvite-crystallization, membrane contactors, air-stripping, ionic exchange, electrodialysis, direct osmosis, etc.). Recently, resource recovery processes have been extensively developed and investigated to optimize their operation.

Reclaimed water can be used for recharging aquifers, irrigation in agriculture and cooling applications. Potential risks posed by the use of reclaimed water – and of other recovered wastewater resources – must be assessed and managed during the lifecycle of the application. For example, membrane separation processes are recognised as suitable for this application to remove pathogens and particles to ensure water quality.

Traditional WWTP design is based on effluent quality requirements and investment costs, with energy efficiency being only rarely considered. Larger facilities exhibit lower normalized electric consumption than smaller WWTPs, and older ones normally consume more than modern facilities (although is process dependent). For instance, in Spain it is possible to find facilities with specific electric consumptions 5-10 times higher than in modern and optimized facilities. This clearly reflects the great margin for potential energy savings.

Electricity consumption at WWTPs can be reduced by improving the processes and their operation, as well as through mechanical equipment improvement. The aeration of the biological process is the major electricity consumer; thus, control strategies have been deployed to its optimization. Also, less oxygen-demanding process alternatives have been explored, like the simultaneous nitrification-denitrification operated at very low dissolved oxygen concentration. Partial nitritation and deammonification processes with low oxygen consumption per nitrogen load removed, are especially suited for treating supernatant from sludge dewatering units. However, these low energy solutions might have a downside with direct greenhouse gas GHG emissions, especially N2O.

Anaerobic digestion of sludge, usually applied in large WWTPs, produces biogas that can generate both electricity and heat for local use or external use, through combined heat and power production, or liquefied biogas for external use. It is also possible to increase biogas production through co-digestion of external substrates, advanced control or sludge pre-treatment. Thermolysis processes, piloted for sewage sludge treatment, enable also waste-to-chemicals applications.

There are also other possibilities for energy recovery at WWTPs, such as thermal energy via heat exchangers and heat pumps, hydropower generation using turbines, and heat from sludge incineration. Energy can be also recovered by anaerobic digestion of microalgae grown in nutrient-rich wastewater.

In this paper, the transition towards sustainability and water-smart circular economy is illustrated showing how current WWTPs can be turned into Water Resource Recovery Facilities (WWRFs). The incorporation of sustainable pathways and technologies, make energy-positive facilities achievable, thus, reducing their climate impact.

Keywords
Circular economy, resource recovery, sustainability, wastewater treatment plant, water resource recovery facility.

1 INTRODUCTION

The main target of wastewater treatment plants (WWTPs) is to remove pollutants from wastewater in order to protect human health and the receiving natural aquatic ecosystems (Metcalf & Eddy, 2013). To achieve this purpose, these facilities feature a sequence of treatment processes that require significant input of energy and chemicals, producing a large amount of sludge which requires further treatment (Veera, 2021). In this wastewater management paradigm, wastewater is considered a waste.

A decade ago, a new paradigm emerged, suggesting that municipal wastewater is a source of resources, particularly reclaimed water, materials (e.g., nutrients) and energy (Neczaj and Grosser, 2018). Moving towards this new paradigm, the wastewater sector is contributing to the Circular Economy (CE). A CE system aims at improving the productivity of resources by keeping products, materials and infrastructure in use for longer than in the traditional linear 'take-make-consume-waste' economic model. CE has been promoted by policymakers in (e.g., European Commission 2020) and adopted by many industries (Mhatre et al., 2021) during past decade. The concept of water-smart Circular Economy (CE) brings further attention to water, resources in water and water-related ecosystems in context of CE (Salminen et al., 2022).

Resource recovery is not something new to the wastewater treatment sector, in fact, at some facilities it has been practiced for many years. The use of anaerobic digestion process to produce biogas as energy recovery strategy together with the application of the digestate (stabilized biosolids) as organic fertilizer has been practiced with success for over 100 years in different parts of the world (Pikaar et al., 2020). Potable drinking water has been produced from wastewater for more than 50 years in the wastewater treatment plant (WWTP) of the capital of Namibia (Windhoek). Namibia is one of the most arid countries in Africa, and most of the little rain that does fall is lost to evaporation, thus, reused water was sought as alternative water source to secure water supply in shortages. To guarantee healthy and high-quality drinking water, the WWTP treatment train was designed as a sequence of state-of-the-art barriers: ozone treatment, ultrafiltration membranes and residual chlorination (Veolia, 2014). This sequence of treatments has been coupled with rigorous monitoring programs to achieve and assure safe drinking water to population. These facts evidence that resource recovery technologies exist and have been practiced successfully at full-scale facilities for many years.

However, in global terms worldwide, only a small fraction of the resources that are conveyed within wastewater are recovered (Pikaar et al., 2020). It is important to highlight that reducing the energy consumption at full-scale facilities and recovering water, nutrients and energy, the wastewater treatment sector is reducing its contribution to greenhouse gas emissions (GHG) and thus its impact on climate change. GHG emissions from WWTPs are mainly associated with the high energy consumption of the facilities as well as the direct emissions of methane (CH4) and nitrous oxide (N2O) (Ye et al., 2022). Taking action to minimize the climate change is urgent, as its negative effects are so evident that can be experienced every year in the urban water cycle itself, with higher frequency of extreme weather events (floodings, droughts), combined sewers overflows, sea level rise, water shortages, and water quality deterioration issues.

Innovative cost-effective processes and strategies that allow resources to be recovered while meeting effluent quality requirements should be deployed at pilot, demonstration and full-scale, to demonstrate that they really work under real-life conditions as to date most research has been limited to the laboratory (Krueger et al., 2020).

Life cycle assessment (LCA) has been widely used to assess the environmental dimension of sustainability of resource recovery from wastewater alternatives, resulting in many papers published in recent years. However, these studies are usually case-specific and as the review of Lam et al. (2020) highlight, there is a need to improve the methodological consistency in these studies as well as to ensure the transparency of inventory and methods among other issues.

In this paper, the transition towards sustainability and water-smart circular economy is illustrated showing how two current WWTPs, of completely different scales (small ≤ 2.000 and large ≥ 100.000 P.E.), can be turned into Water Resource Recovery Facilities (WWRFs). The incorporation of sustainable pathways and technologies, make energy-positive facilities achievable, thus, reducing their climate impact.

2 WWTPS DESCRIPTION

Figure 1 shows the layout of two completely different size WWTPs that will be used as case-base to propose modifications to transform them into WRRFs levering the existing infrastructure. As can be seen both WWTPs are based on activated sludge process.

Figure 1a shows the typical configuration for a large-size facility (~ 100.000 P.E.). Its water treatment line includes standard pre-treatment, primary settler to remove particulate organic matter from the water (to allow its valorisation in the anaerobic digester), organic matter and nutrient removal via biological processes featuring an A^2O process for enhanced biological phosphorus (P) removal, which will be complemented by chemical precipitation after the secondary settler to precipitate the soluble P that has not been previously removed, a sand filter that will allow the removal of particles that have not been retained previously enabling to reach the strictest P limits by eliminating the organic P contained in those particles, and finally UV disinfection prior to discharge the treated wastewater into the natural aquatic environment. The sludge line is mainly composed by a gravity sludge thickener, followed by a anaerobic digester that will generate biogas from the organic matter that receive from both settlers, the stabilised sludge will be dewatered mechanically, resulting in a sludge that can be evacuated by truck from the facility. Note that the gravity settler and the mechanical dewatering produce a reject water rich in nutrients that is returned to the water line.

Effluent discharge limits for the large-size WWTP include DBO_5<25 mg/L, DQO<125 mg/L, SS<35 mg/L, N_T<10mg/L and P_T<0.2mg/L.

Figure 1b shows a small-size WWTP (~ 2.000 P.E.). These types of facilities are much simpler, and usually the sludge line is simple composed by a sludge thickener. The water line features an activated sludge process, operated at high cellular retention times to allow the sludge to be somewhat stabilized, P-removal is accomplished via chemical precipitation and nitrogen (N) is not removed (i.e., the process and its operation is not designed for (biological) N removal, and only the N removed in that contained in the excess sludge).

Effluent discharge limits for the small-size WWTP include DBO_5<25 mg/L, DQO<125 mg/L, SS<35 mg/L, and P_T<2mg/L

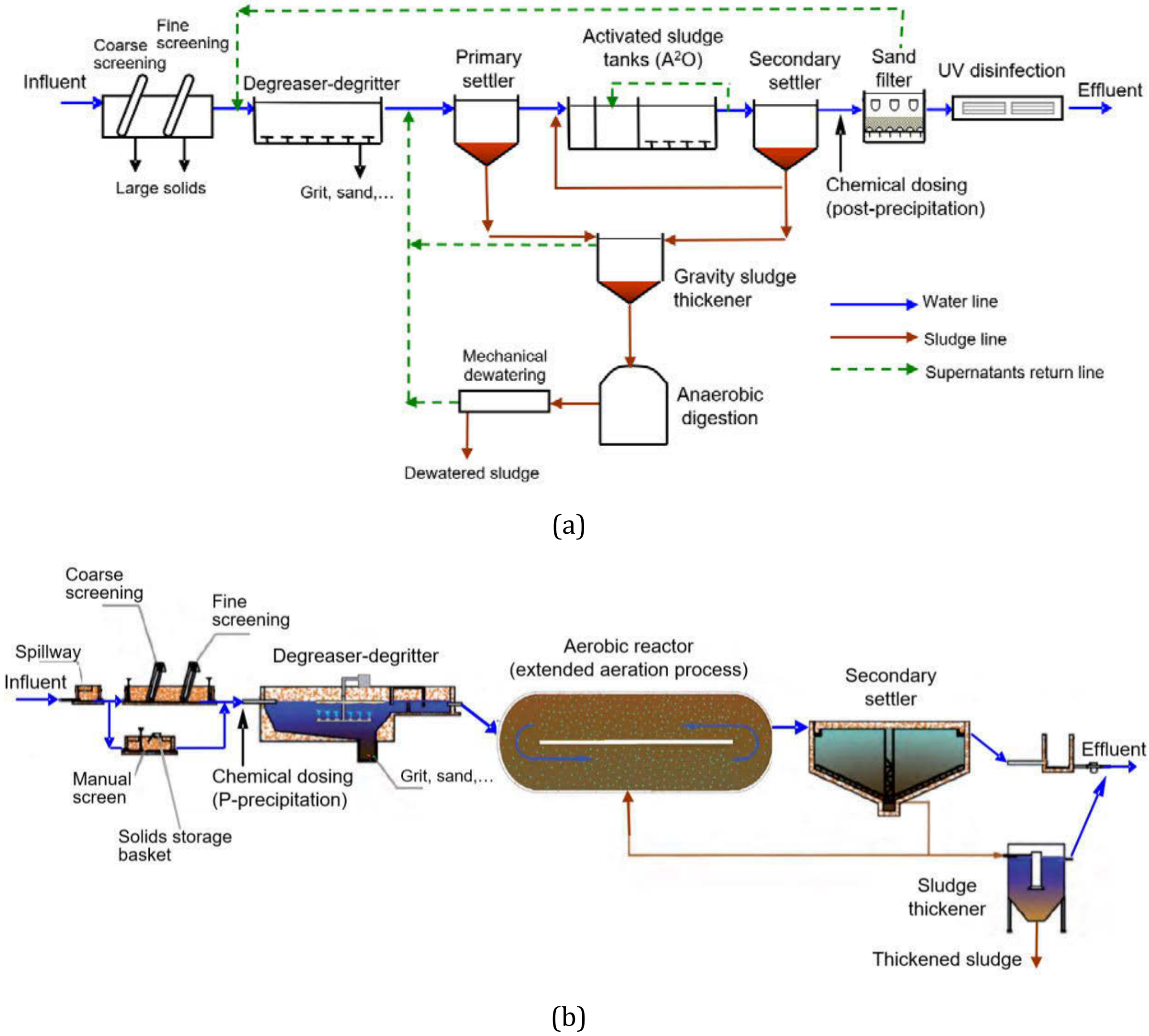

Figure 1. Layout of two typical WWTPs configurations: (a) Large-size WWTP ~100.000 P.E. (b) Small-size WWTP ~2.000 PE

3 RESOURCE RECOVERY PROCESSES FOR SUSTAINABLE WASTEWATER TREATMENT

3.1 Large-size WWTP

3.1.1 From raw data to quality checked data fitted for purpose

The specific electrical energy consumption among different WWTPs is quite variable. In a survey of more than 140 WWTPs in Spain specific energy consumptions ranging from 0.1 to higher than 3.5 kWh/m³ were reported (Ferrer *et al.*, 2016). Factors like the biotechnological process implemented in the WWTP, its configuration, the effluent quality requirements or its treatment capacity significantly impact the specific energy consumption. Conventional treatment technologies usually range from 0.3 to 0.6 kWh/m³ (Sarpong and Gnaneswar, 2021). Therefore, WWTPs exhibiting noticeably higher specific consumptions have (in principle) a significant margin of energy savings.

The distribution of energy consumption among the different parts of a WWTP is approximately as follows: 44% aeration tank, 15% sludge thickening, 12% anaerobic digestion, 12% pumping, 12% deodorization. Electricity consumption at WWTPs can be reduced by optimizing the processes and their operation, as well as through mechanical equipment improvement (eg., using more efficient pumps, blowers and diffusers).

Since aeration is the most energy-intensive process (accounting in some cases more than 50% of the total energy consumption of the WWTP), efforts should focus on this process to achieve significant energy savings. Although less oxygen-demanding process alternatives exist (e.g., simultaneous nitrification-denitrification, ANaerobic AMMonium OXidation – ANAMMOX) and these biological processes have been explored even implemented in full-scale facilities, they have an important downside related to the emissions of direct greenhouse gas (GHG): N_2O. This potent GHG has a global warming potential 265 times greater than CO_2 (Myhre *et al.*, 2013), it is very persistent in the atmosphere (mean residence time > 100 years) and is considered the greatest ozone-depleting gas in the atmosphere (Ravishankara *et al.*, 2009). Since GHG emissions are a major cause of global warming, these low oxygen demand biological processes are not proposed to save energy in the WWTP upgrade. Therefore, the reduction in the energy consumption of the aeration process will be achieved via:

- Reducing the amount of organic matter that reach the aerobic tank which will lead to lower aeration needs in the biological reactor. This can be accomplished by enhancing the primary settling tank performance (as it will be discussed later).
- Using more efficient diffusers and blowers/compressors to supply the required oxygen to the aerobic tank and sizing the equipment in such a way that it is possible not only to meet the peak oxygen needs of the biological process (that traditionally was the only issue taken into account in its design), but also during night-time wastewater flow satisfy just the minimum oxygen needs without exceeding the amount required (thus, avoiding energy waste during nights as well as in other periods of low organic load).
- Adjusting the amount of oxygen supplied into the aerated tank according to the biological (and mixing) needs, via process control.

Energy from the wastewater can be recovered from the influent organic matter that it contains, from the kinetic energy of the flow in motion and also from the heat content of the wastewater.

Anaerobic digestion is the best option for recovering energy from the organic content of the sludge gathered in the primary and secondary settling thanks of medium and large-size WWTPs. During the anaerobic digestion of the organic compounds a biogas is produced (mainly composed by 60-70% CH_4 and 30-40% CO_2), which has a heating value around 37,3 KJ/m^3. Thus, using the biogas as a fuel source, electricity can be generated. The recovered energy is usually used directly in the WWTP itself. The biogas production can be increased by:

- Increasing the removal of biodegradable organic compounds in the primary settler (which typically is around 40% of the particulate material), with the added benefit of reducing the energy consumption in the aerobic reactor as less organic matter will reach the aerobic reactor via the water line, thus, less oxygen will be required by the microorganisms, and less energy will be consumed. This can be achieved by the implementation of micro-sieving followed by cloth media filter (reaching 80-90% of particulate material retention), or ultrafiltration membranes (100% of particulate material retention and part of the soluble organics are also retained since the pore size of the membranes is around 0.03 μm) after the primary settler. Although the first option (micro-sieving followed by cloth media) has a lower particulate retention capacity, it has a significative lower capital investment than the membranes, thus the payback would be noticeably shorter.

- Incorporate sludge thermal pre-treatment to increase its degradability. Thermal hydrolysis process has been successfully applied in full-scale facilities, reporting an increment in biogas production ranging 20 to 50% (Linh *et al.*, 2021).
- Adding external biodegradable organic compounds (e.g., food waste or other energy-rich organic wastes) which can also supply missing nutrients to the microbiota of the digester, thus favouring the anaerobic degradation process. This will provide an extra revenue generation while reducing odour problems in the streets associated with food waste in the garbage containers as well as the arrival of organic compounds to landfill.

Effluent water heat recovery with heat pumps. The implementation of heat pumps after the treatment train will allow to recover heat that can be used to provide hot water within the facility, to dry the sludge and to heat/cool the administrative, maintenance and utility buildings within the facility even residential buildings that are close to the facility.

Installing turbines to take advantage of kinetic energy of the effluent of the WWTP. Recovering energy from the flow of wastewater facility using micro-hydro-power (MHP) turbines has been shown to be a viable strategy to achieve energy savings at facilities with large flows rates and/or large available heads, the latter being relatively uncommon (Power *et al.*, 2017). According to these authors, traditional MHP turbines (eg., Kaplan and Francis) are viable for applications with large flow rates and power-production capacities exceeding 10 kW. Pump-as-turbines (PATs) are a low-cost alternative for MHP energy recovery allow a shorter payback but lower efficiencies (close to 60%) in contrast with traditional turbines (with efficiencies close to 80%). Splitting the flow through several turbines in parallel allows to increase the average efficiency of the MHP recovery system by allowing them operate close to their maximum efficiency point despite daily wastewater flow variations. The power recovery can be estimated as P (kW)=ρ (Tn/m^3) g (m/s^2) Q (m^3/s) H (m) e (%), being ρ the fluid density, g the gravity acceleration (9.81 m/s^2), Q the flow rate, H the available head at the turbine and e the overall efficiency of the MHP system. Therefore, for a WWTP serving 100.000 PE if the available head is lower than 5 m, PATs would the preferred option for recovering energy as long as low-cost low-head turbine solutions do not exist on the market.

Harvesting on-site wind and solar power. Although this is not energy from the wastewater, this option would allow to take advantage of the large space that these facilities normally have. Evidently, the techno-economic viability of their installation depends on local weather conditions.

3.1.2 Phosphorus recovery

P- recovery from wastewater has attracted scientific research interest for several reasons:

- It is a nutrient essential to life: humans, animals and plants need P. It is an important component of fertilizers used in agriculture.
- It is mainly obtained from phosphate rocks. This natural reserve has been predicted to be exhausted within the next century (Li *et al.*, 2019).
- If not removed from wastewater, its discharge into aquatic environments promotes their eutrophication.
- It can cause uncontrolled precipitation within the WWTP, increasing rugosity and reducing the effective cross-section of pipelines, increasing the energetic costs associated to pumping, even blocking pipes (Neethling and Benisch, 2004).

Traditionally P-removal is accomplished in WWTPs biologically (enhanced biological phosphorus removal, EBPR), chemically or a combination of both methods (Cornel and Schaum, 2009). Many different processes to recover P from different parts of a WWTP (effluent, digested sludge, sludge ash,…) have been sufficiently studied to be implemented and tested at full-scale. A description of a wide variety of technologies to recover nutrients from wastewater (discussing their potentials and limitations) can be found in Robles *et al.* (2020). The success of any P-recovery technique is highly dependent on the amount and the quality of the recovered product (usually a marketable fertilizer) which influence its final price. Taking into account investment and operational costs, the production costs of the ecological P-rich fertilizer of most recovery technologies developed have been calculated to double the production costs of the industrial fertilizer (Schaum *et al.*, 2019).

Thus, to recover P from wastewater in the large-size WWTP, a modification in the sludge line configuration is proposed, which enables a noticeably reduction in P precipitation in anaerobic digesters (> 40%, Bouzas *et al.*, 2019) with minimal structural modifications in the facility. The new configuration is shown in Figure 2 and consists in recirculating part of the thickened sludge to elutriate it in the gravity thickener. In this way, polyphosphate accumulating bacteria will release the P stored intracellularly towards the liquid phase, thus reducing the P-load to the anaerobic digester.

P will be recovered as struvite in a crystallizer should be constructed and that would receive two P-rich flow streams: the supernatant from the primary thickener and the centrifuge filtrate. Struvite is composed by phosphate, ammonium and magnesium ions in equal molar concentrations ($MgNH_4PO_4 \cdot 6H_2O$) and it is precisely a common scale that forms within the digester and pipe walls. The crystallization of struvite (magnesium ammonium phosphate - MAP) is nowadays considered one of the best alternatives to recover both ammonia nitrogen (N) and phosphate phosphorus (P) from wastewater (Robles *et al.*, 2020). It is a cost-effective process that yields a high-quality product that can be used as ecological and valuable slow-release fertilizer. The higher struvite production the lower demand for conventional fossil-fuel based fertilizers.

Another potential option for recovering P precipitate is from the back-wash water of the sand filters. In this case, its suitability depends on P concentrations in the back-wash, thus is very case-specific and not as general as the centrifuge filtrate obtained from the anaerobic digester effluent. The lower the effluent P limit the higher P concentration in backwash waters. To obtain the precipitate, the solids should be settled, thickened and dewatered. That precipitate should then be further processed.

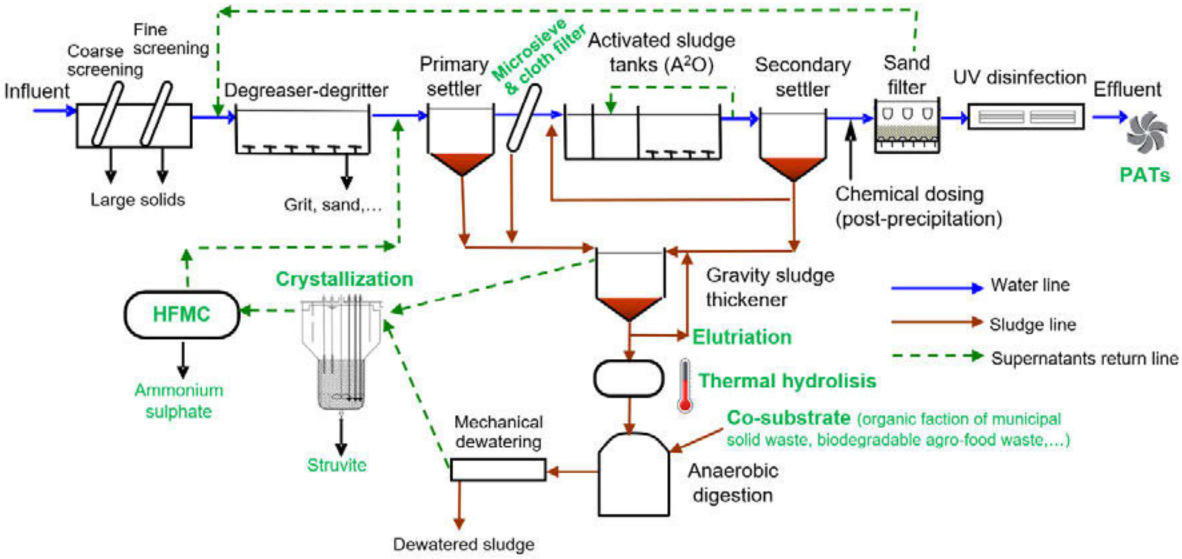

Figure 2. Large-size WWTP layout showing the modifications to turn it into a WRRF.

3.1.3 Nitrogen recovery

N is a nutrient present in many commercial fertilizers. Despite being the most abundant gas in the atmosphere, its conversion into ammonium through the Haber-Bosch process is very energy-demanding. Its removal from wastewater is usually accomplished via biological nitrification-denitrification processes requiring high-energy consumption due to the oxygen that must be supplied the nitrifying bacteria.

The struvite crystallization, previously proposed to recover P from the reject water from anaerobic digestion also allows recovering part of the nitrogen present in this return-stream. As reported in Robles *et al.* (2020) P-recovery efficiencies ranging from 80 to 90% of the P-contained in the reject water from the anaerobic digester but only from 20 to 30% of the ammonia nitrogen present in this return-stream.

Therefore, other N-recovery process should be implemented in the large-size WWTP to recover the ammonia nitrogen and avoid its return to the waterline, where it would be removed via nitrification-denitrification increasing the energy consumption. Among the wide variety of technological processes existing, the hollow fibre membrane contactor (HFMC) has emerged as a promising technology for nitrogen recovery (as ammonium sulphate, which is a marketable fertilizer) from high nitrogen streams. Noriega *et al.* (2021) have shown that HFMC application to the reject water from the anaerobic digestion of a full-scale WWTP it is economically viable (as the expenses are offset by the benefits), with the great advantage of significant reduction in the global warming potential.

3.1.4 Water recovery

Water is the most obvious resource that can be recovered from wastewater. It has been practiced for many years for agriculture irrigation purposes, thus, contributing to alleviate the local water stress. In this way, higher quality water river resources are released for domestic drinking water purposes.

Although the reuse of treated wastewater for domestic direct potable use is technically possible, is not usually practiced as it is forbidden in most parts of the World and there is also the “yuck factor” of customers. Just the notion of drinking treated wastewater triggers this emotional discomfort on people. There are very few cases, like in Windhoek (Namibia), where potable use has been put into practice, and in these cases to guarantee the maximum the customer’s health a sequence of barriers (stages) has been deployed in treatment chain leading to a multi-barrier approach.

Non-potable uses are generally more acceptable by people than potable uses because the underlying perception of health risk associated with wastewater is significantly lower: agriculture, artificial wetlands, groundwater replenishment, land irrigation, industrial purposes, toilet flushing, …

Water can be recovered from wastewater together with nutrients and a reduction in global energy consumption of the facility, via fertigation. This is a reliable and controlled source of water and nutrients that are supplied simultaneously to agriculture crops and plants, and significantly reduces GHG emissions as it avoids energy-intensive wastewater treatment process to remove nutrients, that would be later supplied to crops in the form of fossil-fuel industrial fertilizers (Mainardis *et al.*, 2022). These authors recommend assessing the correspondence between facility treated effluent in terms of quality and flowrate and the agriculture irrigation demand before the adoption of fertigation.

3.2 Small-size WWTP

Small-size facilities are considered those that serve a population of less than or equal to 2.000 PE. Despite treating a relatively small wastewater flow, in global terms they are important as they are many facilities in this range size, for instance, only in Spain there are about 6000 municipalities with a population size in this range.

This type of facilities is usually designed with a simplified configuration to allow a robust operation with very little staff. For this reason, high maintenance requirements in terms of expertise (and cost) are no feasible for these facilities. Therefore, no advanced resource-efficiency technology would really be feasible in practice. Not even the use of PATs for recovering energy from the flow would be profitable unless the available head would be close to (or higher than) 5 m. According to Llácer-Iglesias *et al.* (2021), recent developments in small scale hydropower indicate that 100 W can be considered a reasonable cut-off value to suggest the technical feasibility of the installation of PATs in a WWTP.

Therefore, the best solution that could be done in these cases is increasing resource-efficiency by means of automatic control and outsourcing the further processing of sludge in a centralized plant that makes use of energy and nutrient content of the sludge. Additionally, if the climatic conditions allow it, harvest on-site wind and solar power.

Another option for this type of facilities, but not leveraging the existing infrastructure, would be to substitute the mainstream biological aerobic process by an anaerobic bio-membrane reactor (AnMBR) in combination with fertigation (as described in Jiménez-Benítez *et al.*, 2020). This configuration (Figure 3) will fit within the available space (the AnMBR is a compact solution) and will significatively reduce the CO_2 emissions due to both the organic matter valorisation and the minimization of the mineral fertilizer requirements. Moreover, the biogas production in the AnMBR could be easily increased by incorporating the OFMSW as co-substrate for the anaerobic process.

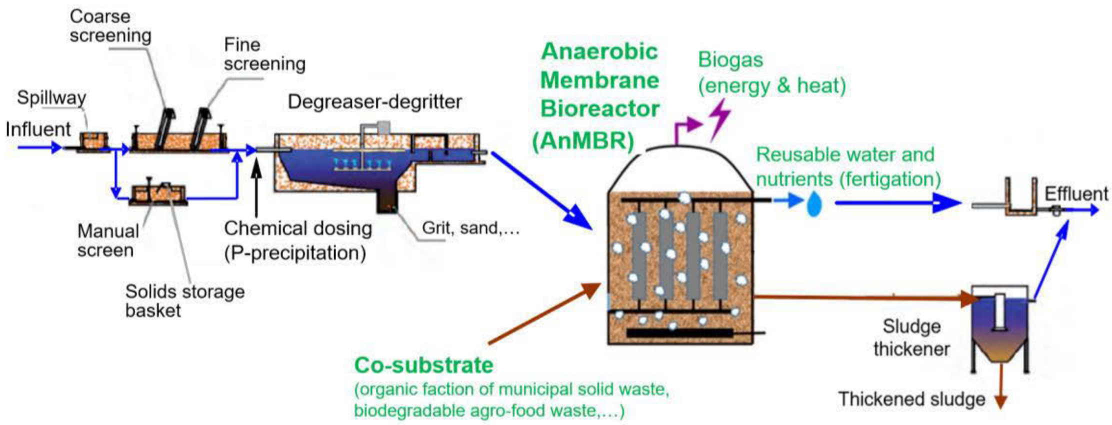

Figure 3. Small-size WWTP layout showing the modifications to improve its resource recovery capabilities.

4 CONCLUSIONS

In this paper, the transition towards sustainability and water-smart circular economy has been illustrated showing how two extremely different sizes WWTPs can be turned into Water Resource Recovery Facilities (WWRFs). The main conclusions that can be drawn are as follows:

- The best way to save energy is not needing to use it:

   - therefore, diverting organic matter and nutrients from the water line to the sludge line for its anaerobic treatment should be promoted, when possible,
   - check all the pumping systems in the facility, as well as all the intensive-energy processes to find inefficiencies and solve them.
- A nice choice for increasing resource-efficiency is to implement advanced process control, for instance by reducing the aeration supplied and the chemicals dosed or by increasing the production of biogas.
- The high nutrient content in the reject water from the anaerobic digester makes this flow-stream ideal for implementing nutrient recovery techniques.
- Every WWTP, regardless of its size and configuration, can improve its resource recovery capability.
- Resource recovery in small-size WWTP is more tricky than larger ones, since their simplified configuration (to enable its operation with very little staff) and their lower influent flowrate, limit the techno-economically sensible alternatives. In most cases, further sludge processing would be preferable to do it in large-scale centralized plants off-site.
- Many different resource recovery alternatives already exist, but the optimal conversion is case-specific and should leverage the existing infrastructure.

5 REFERENCES

[1] Bouzas A., Martí N., Grau S., Barat R., Mangin D., Pastor L. (2019) Implementation of a global P-recovery system in urban wastewater treatment plants, Journal of Cleaner Production, 227, 130-140. 10.1016/j.jclepro.2019.04.126

[2] Cornel P., Schaum C., 2009. Phosphorus recovery from wastewater: needs, technologies and costs. Water Sci. Technol. 59, 1069e1077. https://doi.org/10.2166/ wst.2009.045.

[3] European Commission (2020) A new circular economy action plan – for a cleaner and more competitive Europe. Brussels, Belgium.

[4] Ferrer J., Aguado D., Barat R.; Serralta J.; Lapuente E.J. (2017). Huella Energética en el Ciclo Integral del Agua en la Comunidad de Madrid (Energy footprint in the Integral Water Cycle in the Community of Madrid (Spain)). Fundación Canal. Canal Isabel II. ISBN 978-84-945176-8-6

[5] Jiménez-Benítez A., Ferrer F.J., Greses S., Ruiz-Martínez A., Fatone F., Eusebi A.L., Mondéjar N., Ferrer J., Seco A. (2020). AnMBR, reclaimed water and fertigation: Two case studies in Italy and Spain to assess economic and technological feasibility and CO2 emissions within the EU Innovation Deal initiative, Journal of Cleaner Production,270,https://doi.org/10.1016/j.jclepro.2020.122398

[6] Krueger B. C., Fowler G. D., Templeton M.R., Moya B. (2020). Resource recovery and biochar characteristics from full-scale faecal sludge treatment and co-treatment with agricultural waste, Water Research, 169, https://doi.org/10.1016/j.watres.2019.115253

[7] Lam K. L., Zlatanović L., van der Hoek J.P. (2020). Life cycle assessment of nutrient recycling from wastewater: A critical review, Water Research,173, https://doi.org/10.1016/j.watres.2020.115519

[8] Llácer-Iglesias R.M.; López-Jiménez P.A.; Pérez-Sánchez M. (2021) Hydropower Technology for Sustainable Energy Generation in Wastewater Systems: Learning from the Experience. Water, 13, 3259. https://doi.org/10.3390/w13223259

[9] Li B., Boiarkina I., Yu W. , Huang H. M., Munir T., Wang G. Q. , Young B. R., (2019). Phosphorous recovery through struvite crystallization: Challenges for future design, Science of The Total Environment,2019, 1244-1256, https://doi.org/10.1016/j.scitotenv.2018.07.166

[10] Linh Ngo P., Udugama I. A., Gernaey K.V., Young B.R., Baroutian S. (2021). Mechanisms, status, and challenges of thermal hydrolysis and advanced thermal hydrolysis processes in sewage sludge treatment. Chemosphere, 281,13089.

[11] Mainardis M., Cecconet D., Moretti A., Callegari A., Goi D., Freguia S., Capodaglio A.G.(2022). Wastewater fertigation in agriculture: Issues and opportunities for improved water management and circular economy, 296, 118755. doi: 10.1016/j.envpol.2021.118755

[12] Mhatre, P., Panchal, R., Singh, A. and Bibyan, S. (2021): A systematic literature review on the circular economy initiatives in the European Union. Sustainable Production and Consumption, 26, pp. 187-202.

[13] Metcalf & Eddy (2013. Wastewater Engineering: Treatment and Resource Recovery, 5ed. ISBN: 978-0073401188

[14] Neczaj E., Grosser A. (2018). Circular Economy in Wastewater Treatment Plant–Challenges and Barriers. Proceedings.; 2(11):614. https://doi.org/10.3390/proceedings2110614

[15] Neethling J.B., Benisch M. (2004) Struvite control through process and facility design as well as operation strategy. Water Sci Technol; 49 (2): 191–199. doi: https://doi.org/10.2166/wst.2004.0122

[16] Noriega-Hevia, G; Serralta, J;Seco, A; Ferrer, J. (2021). Economic analysis of the scale-up and implantation of a hollow fibre membrane contactor plant for nitrogen recovery in a full-scale wastewater treatment plant, Separation and Purification Technology, 275,119128. https://doi.org/10.1016/j.seppur.2021.119128

[17] Pikaar I., Huang X., Fatone F., Guest S. (2020). Resource recovery from water: From concept to standard practice, Water Research, 178, 115856, https://doi.org/10.1016/j.watres.2020.115856

[18] Ravishankara A.R., Daniel J.S., Portmann R.W. (2009). Nitrous Oxide (N2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century. Science, 326 pp. 123-125. doi:10.1126/science.1176985

[19] Robles A., Aguado D., Barat R., Borrás L., Bouzas A., Giménez J.B., Martí N., Ribes J., Ruano M.V., Serralta J., Ferrer J., Seco A. (2020) New frontiers from removal to recycling of nitrogen and phosphorus from wastewater in the Circular Economy, Bioresource Technology, 300. https://doi.org/10.1016/j.biortech.2019.122673

[20] Salminen, J., Määttä, K., Haimi, H., Maidell, M., Karjalainen, A., Noro, K., Koskiaho, J., Tikkanen, S. and Pohjola, J. (2022) Water-smart circular economy - Conceptualisation, transitional policy instruments and stakeholder perception. J. Clean. Prod., 334, 130065.

[21] Sarpong G. and Veera G.G. (2022). Energy consumption and recovery in wastewater treatment systems. In Resource Recovery from wastewater: Toward Sustainability. CRC Press. ISBN 978-1771889285

[22] Schaum C., Hubert C., Krause S., Steiniger B. (2022). Phosphorus removal and recovery in water resource recovery facilities. In Resource Recovery from wastewater: Toward Sustainability. CRC Press. ISBN 978-1771889285

[23] Veera G.G. (2022). Resource Recovery from wastewater: Toward Sustainability. CRC Press. ISBN 978-1771889285

[24] Veolia (2014). Veolia installs wastewater plant in Windhoek, Namibia. Membrane Technology, 10, https://doi.org/10.1016/S0958-2118(14)70208-3.

[25] Ye L., Porro J., Nopens I. (2022). Modelling of Fugitive Greenhouse Gas Emissions from Urban Water Systems. IWA Publishing. ISBN: 9781789060454