Editorial

Sustainable Wastewater Management and Treatment

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This Special Issue of *Sustainability* aims to report the recent developments in Sustainable Wastewater Management and Treatment, mainly those focused on improving the overall performance of wastewater treatment plants (WWTPs) in terms of both reducing their environmental impact and integrating them into the urban circular economy. The works presented here show new technologies, processes and operational strategies that lead to a paradigm shift in wastewater management, where the minimization of energy consumption and recovery of valuable resources are key aspects.

Most urban wastewater treatment plants were designed to meet local requirements for effluent quality, while environmental aspects such as energy consumption and resource recovery were not considered [1]. However, in recent years, many efforts have been dedicated to achieving a positive energy balance. This might be achieved by promoting organic matter removal through anaerobic routes, increasing biogas production, reducing aeration requirements, and recovering nutrients [2,3]. The main challenges that existing technologies face in fulfilling these goals are the low concentrations of organic matter and nutrients present in urban wastewater. In this respect, various solutions have been proposed, such as segregation at the source to keep resources as concentrated as possible [4] or the concentration of resources within the WWTP by means of membrane systems [5]. Microfiltration, ultrafiltration, or forward osmosis can be applied to separate the organic matter from the WWTP mainstream and divert it to an anaerobic digester in order to improve the WWTP energy balance (Contribution 1). The stricter the filtration process, the better the effluent quality obtained. However, the retention of salts is also promoted, which could inhibit anaerobic digestion of the retained organic matter. In addition to improving the energy balance of WWTPs, the removal of organic matter through anaerobic processes has the additional advantage of lower sludge production than aerobic processes. This is essential, since sludge management is one of the most critical issues in WWTP operation, representing 25% to 65% of the overall operating costs [6]. Thus, anaerobic digestion is the most used process to indirectly decrease costs associated with sludge dewatering, transport, or drying by reducing sludge production. However, anaerobic sludge digestion technologies are generally present only in WWTPs with a treatment capacity larger than 40,000 inhabitant equivalents. Moreover, its efficiency is limited to 30–40% of dry solids reduction. For this reason, other technologies for reducing sludge generated in situ that could be applied in small WWTPs are gaining attention. Among those technologies, ozonation, which enhances the hydrolysis rate of particulate matter (the limiting step of the degradation of the solid) by sludge disintegration, has been successfully applied at full-scale. In fact, if the implementation of an ozonation unit to reduce sludge production is considered during the design of small WWTPs, overall wastewater treatment costs would significantly decrease (Contribution 2).

Another alternative to diminishing WWTPs' energy consumption is using systems based on the combination of microalgae and bacteria to remove both organic matter and...
nitrogen. In these systems, photosynthesis directly provides oxygen, and no external aeration is needed. Contrary to the activated sludge systems, where bacteria remove nitrogen through nitrification/denitrification processes, with the microalgae–bacteria consortia, nitrogen is removed via assimilation for biomass growth without greenhouse gas emissions [7]. The processes based on microalgae are generally carried out in open raceway ponds requiring larger land areas than conventional systems. Therefore, despite being eco-friendly and low-cost technologies for wastewater treatment, their application would be restricted to small communities, where enough land is available. The potential application of microalgae should focus not only on nutrient removal but also on the removal of organic pollutants due to the ability of these microorganisms to remove personal care products, pharmaceuticals, pesticides, and industrial products [8]. For example, Contribution 3 shows that the marine microalga *Tetraselmis suecica* can remove phenolic compounds, which are hardly biodegradable in conventional biological systems.

WWTPs are designed and operated in such a way that they can comply with the discharge limits under fluctuating influent conditions. In the past, this purpose was achieved by oversizing the WWTPs and overdosing on the oxygen required. Nevertheless, the development of mathematical models and real-time control systems have allowed optimizing the design and operation conditions of WWTPs to maintain a compromise between the effluent quality and the treatment costs. Models are valuable tools to understand how the operational parameters affect the effluent quality, as Contribution 4 shows. They can also be used to upgrade or redesign WWTPs to maximize the valorization of products recovered from the wastewater [9]. For example, aeration accounts for 50% to 60% of the energy consumption during wastewater treatment. For this reason, the research on real-time control systems is mainly focused on aeration to save energy while maintaining a suitable effluent quality. Since the airflow rate can be fitted to oxygen demand, implementing dissolved oxygen (DO) and aeration control systems can save 25 to 40% more energy than manually controlled systems [10]. The recent availability of reliable ammonium sensors has led to their incorporation into aeration control loops, allowing the development of more advanced aeration control strategies that enhances energy savings [11]. However, these sensors are expensive, so they could be replaced by soft sensors developed using multiple linear regression, neural networks, and oxidation-reduction potential and pH sensors (Contribution 5).

In addition to WWTPs’ energy efficiency improvements, much effort is being carried out to recover the resources contained in wastewater, such as phosphorus, nitrogen, organic fertilizers, water, and methane, due to the increasing awareness of the exhaustion of non-renewable natural resources. As previously mentioned, the organic matter contained in wastewater is currently mainly revalued as methane through the anaerobic digestion process. Even though anaerobic digestion is a mature and sustainable technology for organic matter revaluation, recent studies indicate the convenience of exploring other technologies aiming to produce higher-value end-products, such as polyhydroxyalkanoates (PHAs) [12]. PHAs are biodegradable polymers synthesized by numerous bacteria, accumulating as intracellular carbon and energy reservoirs that could be used to replace conventional plastics. Currently, the large-scale production of PHAs is carried out using pure culture microorganisms and high-cost substrates, making their production price non-competitive compared to petrochemical-based plastics. All these issues can be overcome by using mixed microbial cultures (MMC), which do not require sterilized conditions and are able to produce PHAs from the organic matter present in wastewater. Up to now, this option has been tested at a pilot-scale using biomass with PHA-accumulation potential from municipal wastewater treatment and fermented waste sludge as feedstock for PHA accumulation [13]. PHAs production using MMC is not only limited to recovering organic compounds from urban wastewaters, but it can also be carried out using industrial wastewaters. In fact, Contributions 6 and 7 demonstrate the feasibility of enriching a MMC with a PHA storage ability to valorize fish-canning industrial wastewater, which is generally difficult to treat by biological processes due to its high salinity.
Growing demand for high-quality water, together with the impacts of climate change, has increased the number of regions in the world that suffer water scarcity or stress. This scenario has promoted the development of technologies able to use non-conventional water resources, such as seawater and treated urban wastewater, to generate drinking water at a full-scale worldwide [14]. In the case of countries with access to the sea, where both seawater and treated urban wastewater are available, the criteria for choosing between one or the other water source could be based on economic considerations. In this sense, Contribution 8 proposes a methodology to determine which of both non-conventional water resources provides the lowest production costs, depending on the wastewater treatment system used, the capacity of the water generation plant, and the distance to the water source. Water reuse is also promoted in many industrial sectors. Those using cooling tower systems are of special interest due to their high water requirement. Technologies such as reverse osmosis and electrocoagulation, among others, could be used to treat water purged from cooling towers, obtaining a high-quality effluent for reuse (Contribution 9). As a general rule, the technologies that allow achieving a better quality of effluent consume the most energy, so the use of renewable energies would perhaps condition their possible implementation.

WWTPs reduce the concentration of pollutants present in the wastewater to obtain effluents that meet the discharge limits. Nevertheless, WWTPs’ effluents still cause important impacts on the ecosystems of receiving waters. To avoid such impacts, in the future, effluents should receive post-treatment through semi-natural wetland systems, as proposed in Contribution 10, or the treatment efficiency of WWTPs should be improved by implementing new units or changing existing technologies. The treatment efficiency improvement should not be only focused on conventional pollutants but also emerging pollutants. Among them, antibiotics stand out due to the growing concern about the increase of the antibiotic resistance of human pathogenic bacteria in aquatic environments caused by the emission of effluents containing antibiotic-resistant bacteria, antibiotic resistance genes, and antibiotics themselves [15].

Urban WWTPs are a key part of the anthropogenic water cycle. Until now, their role has been to decrease the pollutant load of wastewater in order to reduce the impact of the effluents on the ecosystems. However, their design in the future should be improved to promote resource recovery (energy, fresh water, and other valuable materials) and enhance their treatment efficiency, considering emerging pollutants. In this way, the WWTP concept would evolve from a “treatment system” to a “biofactory” to become an essential part of the sustainable circular economy.

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