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Editorial

Resource Recovery Monitoring and Circular Economy Model in Wastewater

Jolita Kruopienė [1,*] and Marzena Smol [2]

1 Institute of Environmental Engineering, Kaunas University of Technology, 44239 Kaunas, Lithuania
2 Mineral and Energy Economy Research Institute, Polish Academy of Sciences, 31-261 Cracow, Poland; smol@meeri.pl
* Correspondence: jolita.kruopiene@ktu.lt

1. Introduction

Pressure on freshwater resources is constantly growing, while wastewater generation is increasing with population growth and industrial activity. The integration of circular economy (CE) principles into the water and wastewater sector is increasingly recognized as being essential to address global challenges related to resource depletion, environmental degradation, and climate change. Several recent reviews have examined this relationship, highlighting the significant potential for CE practices to transform how water and wastewater are managed. According to Guerra-Rodríguez et al. (2020) [1], wastewater should be viewed as a resource rather than a waste product because there exists the potential to recover valuable resources such as water, energy, and raw materials (e.g., nutrients) which can be reused in various applications, thus contributing to sustainability and resource efficiency. Kehrein et al. (2020) [2] studied the technological aspects of implementing CE principles in wastewater management. They explored how advanced treatment processes can facilitate the recovery of resources like phosphorus and nitrogen, which are critical for agricultural applications. Their review also discussed the challenges of integrating these technologies into existing wastewater treatment infrastructure and the economic benefits of doing so. Gherghel et al. (2019) [3] extend this discussion by examining the role of CE in urban water management. They argued that adopting CE practices, such as water reuse and energy recovery, can significantly reduce the environmental footprint of urban water systems. They also noted the importance of supportive policies, technological innovation, and public awareness in overcoming the barriers to widespread adoption of these practices.

Researchers have proposed various frameworks to guide the implementation of CE principles in the water and wastewater sector. Smol et al. (2020) [4] presented a framework based on the "6Rs" of the CE: Reduce, Reclaim (remove pollutants), Reuse, Recycle, Recover (resources from wastewater), and Rethink. This framework emphasizes not just treating wastewater, but also minimizing its generation and maximizing the value extracted from it.

Evaluating progress towards a circular water economy requires robust indicators. Preisner et al. (2021) [5] proposed a set of indicators covering water resource management, wastewater treatment efficiency, resource recovery, and economic viability. These indicators allow for a comprehensive assessment of how well the water/wastewater sector is transitioning towards a CE model. Moreover, Smol and Koneczna (2021) proposed economic indicators for measuring CE progress at a microeconomic level. These are divided into three groups of cash flow: (i) income (revenues, expenses), (ii) costs, and (iii) investment financing [6].

The practical application of CE principles in the water and wastewater sector is illustrated by numerous research articles and case studies. To provide just a couple of examples, Kruopienė and Žiukaitė (2022) presented a case study where they examined the state and potential for CE practices within the wastewater sector in Lithuania [7]. Kacprzak

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and Kupich (2021) presented a case study where they focused on the application of CE principles in the management of municipal wastewater and sewage sludge in Poland [8].

Thus, the management of wastewater according to the principles of CE is an area where a lot of research is carried out, and although some questions have been answered by previous studies, many questions remain unanswered. Moreover, there are no limits to improvement of practices, technological progress, or changes of attitude.

This Special Issue is dedicated to discussing the ways and opportunities for wastewater to "participate" in the CE. How much and what material and energy resources are recovered? What is the recovery potential? What solutions and technologies are already used in practice, and what is still being developed and tested? How do we monitor resource recovery from wastewater or sewage sludge? What legal frameworks are evolving, and what incentives for resource recovery are being created? The five articles included in this Special Issue, in a broader or narrower way, answer these questions.

2. Main Messages of the Special Issue

The first study included in this Special Issue, the one by Du et al., investigates the impact of nano-sized polyethylene terephthalate (nPET) on the microalgal–bacterial granular sludge (MBGS) process, a green technology for wastewater treatment that aligns with the CE's principles of resource recovery and sustainability. Their research focuses on how different concentrations of nPET affect the removal of pollutants like nitrogen, phosphorus, and chemical oxygen demand (COD) in wastewater. Their results indicate that MBGS can effectively handle nPET concentrations up to 30 mg/L without significant losses in pollutant removal efficiency. However, at higher concentrations (50 mg/L), the process' efficiency declined, and negative effects on microalgae photosynthesis and microbial community structure were observed. MBGS responded to nPET exposure by increasing extracellular polymeric substance (EPS) production, likely as a protective mechanism. Overall, their study supports the potential of MBGS for treating wastewater-containing nano-plastics, and contributes to CE objectives by integrating waste treatment and resource recovery.

The second study included in this Special Issue, the one by Spriet et al. explores the potential of waste heat recovery (WWHR) from commercial kitchen wastewater as a renewable energy solution aligned with CE principles, particularly in reducing carbon emissions and energy consumption. A pilot study was conducted at Penrhyn Castle in North Wales, where a heat recovery system was installed in the kitchen to capture and reuse waste heat from wastewater. Over an eight-month period during the tourist season, the system preheated incoming cold water, leading to an average monthly energy saving of 240 kWh and an annual reduction of 928.8 kg CO_2e. Their study demonstrates the economic viability and environmental benefits of WWHR in commercial kitchens, with a payback period for the investment ranging from 1.7 to 8.2 years, depending on the energy source. Their findings underscore the potential for a broader application of WWHR in the hospitality sector, contributing to CE goals by reducing the reliance on external energy sources and minimizing carbon footprints. Further research was suggested to expand the technology's use across different climates and larger establishments.

The third study in this Special Issue, the one by Collivignarelli et al. addresses the growing environmental challenge of drought by exploring the direct reuse of treated wastewater as a solution for water scarcity. Their research focuses on wastewater treatment plants in Lombardy, Italy, analyzing effluent quality to identify critical pollutants that hinder direct reuse, particularly for irrigation. Their study identifies total nitrogen (TN), ammonia nitrogen (N-NH_4^+), and phosphorus (P) as key pollutants. To enhance effluent quality, they propose, in their study, using biochar filters derived from the pyrolysis of biological sewage sludge, which undergoes chemical activation with KOH. Batch adsorption tests revealed that biochar, particularly when pyrolyzed at 650 °C and 950 °C, effectively removes significant amounts of N-NH_4^+, P, N-NO_3^-, and COD from wastewater. Their results demonstrate that biochar treatment can substantially improve wastewater quality, making it suitable for reuse and contributing to resource sustainability.

Another article by Muscarella et al. describes the ability of zeolites to adsorb and desorb ammonium (NH_4^+) from treated wastewater. Their study investigates how different mineralogical compositions of zeolites, both untreated and treated with sodium chloride (NaCl), affect the desorption of NH_4^+. Their findings reveal that NaCl-treated zeolites exhibit a higher desorption capacity, highlighting the importance of cation exchange and the specific affinity of Na^+ and NH_4^+ for zeolite surfaces. This research is significant for advancing the understanding of nutrient recovery from wastewater, a key aspect of the CE. By recovering NH_4^+ from wastewater and potentially reusing it as a slow-releasing fertilizer, their study contributes to sustainable nutrient management and environmental remediation. The insights gained can guide the development of more efficient and cost-effective zeolitic materials, further promoting the integration of CE principles in wastewater treatment.

The final contribution to this Special Issue, the study by Capodaglio is a review article. It explores the potential of urban wastewater (UWW) to be a valuable resource within a CE framework. It reviews various technologies and methods for recovering water, energy, and materials from wastewater, emphasizing the importance of these practices in addressing urban water scarcity and reducing its environmental impact. The review highlights the challenges posed by traditional linear consumption patterns and outdated infrastructure, which impede the adoption of CE approaches. The author argues for the optimization of existing systems and the implementation of new technologies tailored to local conditions, advocating for a holistic approach to resource recovery that considers economic, social, and environmental factors. The article concludes that adopting circular strategies in UWW management is essential for sustainable urban development and resource conservation.

3. Conclusions

The increasing pressure on freshwater resources has created a critical need for sustainable water management practices. Here, CE principles offer a promising path forward. Recognizing wastewater as a resource rather than a waste product offers substantial opportunities for recovering valuable resources like water, energy, and nutrients. Further analyses and developments of technologies, as well as the monitoring of CE applications in wastewater management, are required.

This Special Issue presents articles that analyze various technological aspects of wastewater treatment so that a subsequent resource recovery and reuse (nutrients, water itself) is possible. The potential for heat recovery is estimated. Case studies from Wales and Italy on energy (heat) recovery and water reuse for irrigation are included. A thorough review article concentrates on urban wastewater mining, covering the approaches to the mining as well as an analysis of the technology involved.

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