Review

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Review

Sustainability of Municipal Wastewater Treatment

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Abstract: The European Parliament had adopted legislative resolution of 10 April 2024 on the proposal for a directive of the European Parliament and of the Council concerning urban wastewater treatment. The reduction of pollution in discharged treated wastewater in the parameters of BOD_5, total nitrogen and total phosphorus was emphasized. Based on these results, it stated that the impacts on the quality of lakes, rivers and seas in the EU are visible and tangible. At the same time, it was emphasized that the sector of urban wastewater removal and treatment is responsible for 0.8% of the total electricity consumption and about 0.86% of all greenhouse gas emissions in the entire EU. Almost a third of these emissions could be prevented by improving the treatment process, better use of sewage sludge and increasing energy efficiency, as well as a higher rate of use of renewable resource technologies. It is also necessary to better integrate treatment processes into the circular economy. Sludge management and water reuse is sub-optimal as too many valuable resources are still being wasted. This review article is focused on sustainable municipal wastewater treatment, innovative and new wastewater treatment processes and technologies (combined and hybrid processes, Anammox, etc. and their use in practice with the aim of increasing environmental and energy efficiency and reducing the carbon footprint. The research is focused on the possibilities of increasing the efficiency of energy processing of sludge, reuse of nitrogen and phosphorus, sludge and reuse of treated wastewater.

Keywords: efficiency; emerging pollutants; energy savings; greenhouse emissions; macronutrients; microalgae; micropollutants; municipal wastewater treatment; sludge management; sustainability

1. Introduction

Wastewater (WW) is essentially water supply of a community after a variety of uses. Regarding origin, WW may be characterized as the liquid and solid waste removed from residences, social and industrial institutions together with groundwater and stormwater depending on the type of sewer collection system.

On April 10, 2024, the European Parliament approved a legislative resolution on the draft directive on municipal wastewater treatment. This directive emphasized the importance of reducing pollution in treated wastewater, especially in terms of biochemical oxygen demand (BOD_5), total nitrogen (TN), and total phosphorus (TP). The directive emphasized that the result of these efforts is a significant improvement in the quality of lakes, rivers, and seas across the EU. However, she also pointed out that the municipal wastewater treatment sector accounts for 0.8% of the EU's total electricity consumption and approximately 0.86% of its greenhouse gas emissions. The directive states that almost one-third of these emissions could be reduced by optimizing the treatment process, increasing the use of sewage sludge, increasing energy efficiency, and expanding the use of renewable energy technologies. In addition, it highlighted the need to better integrate cleaning processes into the circular economy, as current sludge management and water reuse practices are suboptimal, resulting in the loss of valuable resources.

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The Special Issue of Sustainability [2] 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 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. WWTPs are designed to reduce the concentration of pollutants present in wastewater in accordance with the required limits. Despite this, the wastewater discharged from WWTPs as well as their operation still cause a significant impact on the environment. The wastewater treatment strategy should aim at more effective removal of micropollutants and newly emerging substances. More attention should be paid to support the renewal of resources (energy, freshwater and, other valuable materials) and better efficiency of their processing. Such a WWTP concept would lead to a change from a "treatment system" to a "biofactory", which would represent the base part of a sustainable circular economy [2].

The ongoing legislative process of the amended directive on urban wastewater treatment [1] emphasizes not only the protection of the environment, but also the protection of human health. One of the goals of this review paper is to draw attention to the impact of municipal wastewater treatment on sustainable development and human health.

The review article will focus on innovative and novel wastewater treatment processes and technologies and their application in practice with the aim of increasing environmental and energy efficiency and reducing the carbon footprint. The research will focus on the possibilities of increasing the efficiency of the energy processing of sludge, the reuse of nitrogen and phosphorus, sludge, and the reuse of purified wastewater. The authors discuss the challenges posed by conventional wastewater treatment plants in terms of their energy consumption and greenhouse gas emissions. The paper emphasizes the need to integrate wastewater treatment into the circular economy by optimizing resource recovery, improving energy efficiency, and reducing the impact of municipal wastewater treatment plants (MWWTPs) to the environment.

Key innovations, including combined and hybrid processes, Anammox technology, microalgae, wetlands, and the reuse of treated wastewater and sludge, are being explored as viable solutions to increase the sustainability of MWWTPs.

The review also highlights the importance of minimizing emissions of the most serious greenhouse gases, such as nitrous oxide and methane, through advanced operational strategies. It is also focused on energy efficiency of the conventional treatment processes and emphasis one of the main goals in terms of energy recovery – self-efficiency of the wastewater treatment systems. Overall, this paper highlights the critical role of sustainable wastewater management in achieving broader environmental and economic goals.

2. Municipal Wastewater Treatment and Sustainability

Wastewater treatment processes and technologies ensure the removal of various micropollutants with a variety of harmful environmental impacts. In addition, during wastewater treatment, pathogens are destroyed, biomethane is produced and usable bio-substrate for agricultural production is produced. The authors of [3] analysed 46 articles (2000-2023) focusing on the support of wastewater treatment from both economic and environmental sustainability perspectives. The findings announce that wastewater treatment enables sustainable management of natural resources by improving clean water supplies and minimizing pressure on natural resources. It creates pathways for clean energy production and use supporting agriculture significantly.

Many people, especially in developing countries, do not have access to clean water and sanitation services. These inadequate services are the main cause of serious diseases in these countries. The main way to solve these problems is to ensure wastewater treatment. The application of suitable wastewater treatment technologies that are effective, low-cost (in terms of investment and especially in terms of operation and maintenance), easy to operate, and proven are the basis of the strategy of sustainable development in these areas as well. Thus, the treatment and reuse of municipal wastewater represents a sustainable strategy for increasing the coverage of wastewater treatment,

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protecting water resources and assure their rational use, supporting social and economic activities [4].

The authors of [5] performed a sustainability analysis of a MWWTP, using emergency analysis (EmA) for the first time. The evaluated MWWTP consists of mechanical, biological, and tertiary treatment (nitrogen and phosphorus). The costs that are necessary for the operation of the treatment plant as well as the costs associated with the natural assimilation of the pollution released in an emergency state were evaluated. The wastewater treatment process is designed in accordance with the established limits. This study presents an approach to the evaluation of costs related to the natural assimilation of discharged pollution in an emergency state. Because nature can assimilate all the organic load from discharged wastewater, the overall need to support biological degradation will include increased costs related to the necessary dilution of discharged pollutants. This wastewater treatment plant is operated mainly with the use of purchased resources (98.3% of the total emergency budget of the treatment plant) and with negligible use of renewable resources (approx. 1.7% of the total budget). These renewable resources are mainly used to support energy produced from fossil fuels. The environmental costs, which are necessary to ensure treatment processes in conditions of permanent load with contaminants, which must be absorbed by the natural system through discharged wastewater, were evaluated. Thus, in the total emergency budget of treatment processes, the costs of assimilating this load, generally considered free, are considered as additional costs. In this study, a holistic approach was applied to assess the benefits for the treatment plant company and nature to support treatment plant operators in improving wastewater treatment in accordance with legal requirements and the availability of local resources. The results of the EmA analysis of the MWWTP performance as well as related environmental impacts showed that individual wastewater inflows into the MWWTP contribute differently to the environmental impact of the treatment process. EmA analysis allows us to analyse the impact of these inflows according to their quality. The main item of the overall emergency budget is the consumption of electricity, which requires supporting measures for greater use of renewable energy sources. Efforts should be made to reduce electricity consumption and replace fossil energy sources by using renewable ones such as solar and wind energy. The quality of surface water is also affected by the agents used. For example, ferric chloride is the agent with a more significant impact, which requires a greater environmental effort to assimilate the discharged organic load. The high emergency values of energy, which are related to the necessary dilution of polluting substances (biochemical oxygen demand (BOD). chemical oxygen demand (COD), total suspended solids (TSS, TN, and TP) in the receiving water also pointed to the great necessary work of nature to dilute them. Discharged treated wastewater affects the quality of surface waters, which can significantly affect their oxygen levels.

Kiselev et al. [6], also discussed the global challenge for sustainable use and the preservation of water resources and the reduction of energy consumption, i.e., the sustainable operation of WWTPs. The usual "linear model of wastewater treatment (capture and discharge, treatment and disposal) is no longer sustainable. The disposal of some treatment products using a landfill is accompanied by residual energy losses, and the implementation of the 3R (reduction, reuse, recycling) principles of circular economy (CE) becomes a suitable alternative that contributes to the fulfilment of the goals of sustainable development.

The authors of [6] study deal with a holistic approach to the implementation of the circular economy at the WWTPs according to the 3R principles using life cycle analysis (LCA) and material flow analysis (MFA). The authors of this work present the principles of CE indicators construction set using a managerial approach. A set of indicators was designed and studied, an integral index of circularity in three scenarios at real WWTPs. They provide an effective tool for evaluating the progress of CE, which is relatively easy to calculate and interpret.

Reducing the energy consumption of the WWTPs with the removal of organic pollution and nitrogen can be achieved by using a combination of microalgae and bacteria. Since oxygen is produced by photosynthesis, external aeration is not necessary. Nitrogen is removed in these systems by assimilation for biomass growth and without greenhouse gas emissions [7]. V Since these

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environmental-friendly and low-cost technologies require larger areas, their application would be limited to small municipalities with sufficient land available [2].

An important tool for optimizing WWTP operation and reducing energy consumption for aeration (25 to 40%) while maintaining the required quality of discharged wastewater is the use of mathematical models and control systems in real-time. Energy savings can also be achieved by implementing reliable ammonium sensors in aeration control loops and cheaper sensors developed using multiple linear regression, neural networks, and redox potential and pH sensors [8].

The paper [9] deals with the possible use of willow plantations for the sustainable treatment of primary municipal wastewater. Compared to conventional treatment, this method can contribute to reducing the environmental burden and economic costs. The effect of wastewater irrigation on the willow biorefinery potential was studied. Three-year-old willows were used, which were grown on the plot of land, as a reference or irrigated with primary municipal wastewater. Analyses confirmed that the content of Glucan in trees irrigated with wastewater increased by 8%, the content of xylose, mannose, and lignin remained unchanged, and the content of arabinose and galactose decreased by 8 and 29%. Of the total number of 213 phytochemical elements, 14 were significantly enriched and 83 were significantly depleted because of wastewater irrigation. Biomass yield from wastewater irrigation was increased by 200%. The yield of lignocellulosic bioenergy increased to 8.87 t of glucose /(ha year) and 1.89 t/(ha. year) of obtained lignin. Net yields of extracted substances, including phytochemicals of interest, increased to 1.48 t/(ha. year). Maintaining glucose availability shows that sustainable bioenergy production from lignocellulosic can complement wastewater treatment. Extractable phytochemicals suggest the promotion of a new high-biomass phenotype in willow. Combined with lignocellulosic yields, they could contribute to the economic feasibility of this wastewater treatment biotechnology through integration with a sustainable biorefinery.

3. Reducing Greenhouse Gas Emissions in Wastewater Treatment

The environmental impact of wastewater treatment processes has received increasing attention in recent years, especially in the context of global efforts to combat climate change. WWTPs are essential to protect public health and preserve aquatic ecosystems by removing harmful contaminants from sewage and industrial effluents before they are released into the environment. However, the energy intensity of these processes and the associated greenhouse gas (GHG) emissions represent significant challenges for sustainability.

Attention is primarily focused on nitrogen oxide (NO_2) emissions and electricity consumption. However, other significant sources of greenhouse gases, such as sludge handling processes and wastewater streams, are often overlooked.

WWTPs contribute to GHG emissions in several ways, which can be categorized into three main components: direct emissions, indirect emissions, and derived or embedded emissions. Direct emissions are greenhouse gases released directly from processes involved in wastewater treatment. These include nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2), which are released during the biological treatment of wastewater and sludge and subsequently released into the atmosphere [10].

For example, it is estimated that converting just 1% of nitrogen to N_2O can increase the overall carbon footprint of a WWTP by 30% [11].

3.1. Minimization

Nitrous oxide (N_2O) and methane (CH_4) are two primary greenhouse gases (in addition to biogenic CO_2) that are produced during the collection, treatment, and discharge of wastewater. However, the amounts of N_2O and CH_4 generated in a WWTPs can vary widely depending on the specific treatment processes used and the size of the facility [12,13].

Minimizing nitrogen oxide (N_2O) emissions from activated sludge processes offers significant potential for reducing greenhouse gas emissions in wastewater treatment. This can be achieved by excluding certain operating conditions known to contribute to N_2O production. Key conditions associated with increased N_2O emissions include:

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- Low dissolved oxygen (DO) concentrations: Inadequate oxygen levels during nitrification and the presence of oxygen during denitrification can increase N_2O production.
- High nitrite concentrations: Increased nitrite levels in both the nitrifying and denitrifying phases are associated with increased N_2O emissions.
- Low COD/N ratio: A low ratio of chemical oxygen consumption to nitrogen (COD/N) in the denitrification phase can lead to higher N_2O production.
- Sudden changes in pH and oxygen: Rapid changes in pH, dissolved oxygen, ammonia, and nitrite concentrations can disrupt microbial processes, leading to higher N_2O emissions.
- Transient Anoxic and Aerobic Conditions: Fluctuating anoxic (oxygen-free) and aerobic (oxygen-rich) conditions can also trigger N_2O production [14,15].

To effectively reduce N_2O emissions, it is recommended to operate biological wastewater treatment plants with high solids retention times (SRT). This helps keep ammonia and nitrite concentrations low, which are critical to minimizing N_2O production. In addition, the use of large bioreactor volumes can dampen load changes and reduce the likelihood of transient oxygen depletion, further reducing the risk of N_2O emissions. Limiting nitrogen oxide removal through controlled aeration is another strategy that can help reduce emissions. By reducing the rate at which N_2O is removed from the system, microorganisms have more time to consume N_2O, minimizing its release into atmosphere [16].

Minimizing methane (CH_4) emissions in wastewater treatment plants (WWTPs) involves several effective strategies. One key approach is to cover thickening sludge tanks and sludge disposal tanks. By sealing these tanks, gas leaks are prevented, and methane emissions can be captured more effectively. This trapped methane can then be burned with excess biogas in a torch, reducing its release into the atmosphere. It is also crucial to deal with the methane that enters the system through the inflowing wastewater. Methane is often present in the influent because of anaerobic digestion in the sewage system. This external methane load typically represents about 1% of the influent's chemical oxygen demand (COD). Fortunately, a significant portion of this methane—about 80%—is oxidized in activated sludge tanks. This process not only mitigates the impact of methane, but also presents an opportunity to further reduce methane emissions. By optimizing the conditions in the activated sludge tanks, such as ensuring sufficient aeration and maintaining optimal operating parameters, it is possible to maximize the oxidation of the incoming methane and thereby reduce the overall methane emissions from the wastewater treatment process [17].

To effectively minimize CO_2 emissions from WWTPs, it is important to address both direct and indirect sources of CO_2 emissions. Direct CO_2 emissions primarily arise from two main sources: the oxidation of organic matter in biological reactors and the combustion of methane (CH_4). In biological reactors, organic matter is metabolized, releasing CO_2 as a byproduct. In addition, methane, which is produced during wastewater treatment during incineration, releases CO_2. Indirect CO_2 emissions are associated with the WWTP's energy consumption, including electricity used for aeration, pumping, and other operational needs. One of the decisive operational factors affecting CO_2 emissions is solid retention time (SRT) in biological reactors. High SRT values promote endogenous biomass respiration, which increases the oxidation of chemical oxygen demand (COD) to CO_2. Although this process results in higher CO_2 emissions due to greater oxidation of organic matter, it also results in reduced sludge production. Lower sludge production reduces methane formation and consequently reduces CO_2 emissions associated with methane combustion.

Conversely, reducing the SRT can increase the overall energy efficiency of the WWTP, thereby reducing indirect CO_2 emissions related to energy use. However, it is important to balance this approach because very short SRTs can compromise the quality of the treated wastewater. To achieve optimal CO_2 reduction, the SRT should be set to the shortest possible time that maintains an acceptable effluent quality. This balance ensures that both direct and indirect CO_2 emissions are minimized, contributing to a more sustainable and efficient wastewater treatment process [18,19].

3.2. Treatment Technologies

Carbon Sequestration in the Form of Biochar

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Biochar is a carbon-rich substance produced from organic waste materials such as agricultural residues and municipal sewage sludge. It has received significant attention for its high carbon content, cation exchange capacity, large surface area, and stable structure [20]. Biochar and energy can be generated through pyrolysis, a process that involves the thermal decomposition of organic feedstock in an oxygen-free environment [21]. Organic carbon in sewage sludge can be stored in biochar as stable carbon compounds, effectively removing it from the carbon cycle and preventing CO_2 emissions [22]. In the carbon cycle, atmospheric CO_2 is captured by photosynthetic organisms such as plants, which convert it into biomass, which is eventually integrated with the soil as these organisms decompose. This biomass then decomposes and microbial respiration releases CO_2 back into the atmosphere. When biochar is added to soil, its durable nature allows it to remain there for a longer period, helping to reduce greenhouse gas emissions. The pyrolysis process also creates by-products such as bio-oil and syngas, which when burned as fuel release CO_2 that can be absorbed by plants, restarting the cycle of biomass formation. However, biochar production also has some indirect sources of greenhouse gas emissions [22]. The production and properties of biochar, as well as its applications, are influenced by various parameters of the pyrolytic process. These include the particle size of the feedstock, temperature, heating rate, pressure, and residence time. The ideal temperature range for the process is between 300 to 800 °C, with a residence time varying from 30 to 150 minutes [23]. Converting sludge to biochar reduces CH_4 and N_2O emissions, making it a more favorable option than direct application of sludge to agricultural land. This approach addresses the potential health, and environmental risks associated with the use of untreated sewage sludge as a soil conditioner. According to the principles of the circular economy and due to the health risks of raw sludge, the production of biochar from sewage sludge represents a viable alternative for sludge disposal and CO_2 sequestration [22].

Constructed Wetlands

Constructed wetlands (CWs) are synthetic wetlands constructed to treat municipal and industrial wastewater. This technology effectively removes a range of contaminants from wastewater, including nutrients (such as nitrogen and phosphorus), heavy metals, organic pollutants, and emerging contaminants such as steroid hormones, pharmaceuticals, and personal care products [24].

To avoid the negative impacts of the discharged wastewater on the aquatic ecosystem, the discharged wastewater should be additionally treated through semi-natural wetland systems or the efficiency of WWTP treatment should be improved by implementing new units or changing existing technologies [25].

The most used plant species in constructed wetlands for wastewater treatment include Scirpus lacustris, Phragmites australis, Typha latifolia, Typha angustifolia, Nymphaea alba, Potamogeton gramineus, Hydrocotyle vulgaris, Eichhornia crassipes, Lemna minor, Potamogeton crispus, and Littorella uniflora [26]. Canna indica and Glyceria maxima not only excel in nutrient removal, but also show a greater ability to reduce N_2O, CH_4, and CO_2 emissions compared to other plant species used in constructed wetlands [27]. In addition, the incorporation of Rumex japonicus into constructed wetlands significantly reduces N_2O emissions while maintaining a high level of wastewater treatment efficiency [28].

Maucieri et al. [29] investigated factors affecting greenhouse gas emissions in constructed wetlands (CWs), considering variables such as effluent flow and composition, hydroperiod, environmental conditions, and specific plant species used for CW vegetation. CW type significantly affected GHG emissions, with subsurface flow CWs emitting less CH_4 than free water bodies (FWS), while vertical subsurface flow (VSSF) CWs tended to produce more N_2O than tidal flow systems (TWS). A COD/N inflow ratio of 5:1 was identified as optimal for minimizing N_2O emissions while maximizing nitrogen removal in FWS CW. For VSSF CW, this ratio helped to achieve the lowest CO_2 and CH_4 emissions. Intermittent loading of wastewater in CW beds reduced CH_4 emissions but increased CO_2 and N_2O outputs. Temperature showed a positive correlation with CO_2, CH_4, and N_2O emissions, while solar radiation was associated with higher CO_2 and CH_4 emissions. The presence

 doi:10.20944/preprints202408.2051.v1

and type of vegetation in CW also plays a key role, with plants generally increasing CO_2 emissions in all CW types and increasing N_2O and CH_4 emissions in CW VSSF. However, subsurface horizontal flow (HSSF) CWs show significant reductions in CH_4 emissions due to the presence of the plant. The effect of plant species richness on CH_4 emissions has been inconsistently reported, likely due to variations in species used and numbers that affect microbial populations and CW function. Among plant species, *Zizania latifolia* was found to produce significantly higher emissions of CH_4 and N_2O compared to *Phragmites australis*, while no significant differences in these emissions were observed between *Phragmites australis* and *Typha latifolia*. *T. angustifolia* produces significantly lower N_2O emissions than *P. australis*. Despite the potential for increased GHG emissions from vegetation, plants also fix atmospheric carbon through photosynthesis, allowing CWs to act as net CO_2 sinks in many cases [29].

The findings [30] revealed that CH_4 fluxes in biochar-added constructed wetlands (CWs) consistently exceeded those in CWs without biochar, suggesting that biochar can stimulate CH_4 emissions in CWs. Two-way ANOVA and Pearson correlation analyzed further confirmed that biochar application significantly increased CH_4 fluxes. This may be because biochar, as a conductive material, increases direct interspecific electron transfer between methanogens and Geobacteraceae, thereby promoting CH_4 production [30]. However, Chen et al. [31] found that biochar reduced CH_4 emissions in rice double cropping systems by improving soil aeration. Contrasting results may be attributed to differences in redox-active properties, functional groups (such as quinone and hydroquinone as reported by Yuan et al. [32] or changing environmental conditions between aquatic and soil systems. In addition, biochar can increase plant growth, leading to greater plant biomass, which increases the net exchange of CO_2 between the atmosphere and CW [33,34]. However, Spokas [35] reported that CO_2 production was higher for weathered biochar compared to fresh biochar in soil systems during laboratory experiments due to increased mineralization of aged biochar with chemically oxidized surfaces. Thus, differences in GHG emissions between weathered and fresh biochar-supplemented CWs warrant further investigation. Furthermore, CO_2 fluxes increased with increasing COD/N ratio, regardless of biochar application. On the other hand, a higher COD/N ratio can lower pH, leading to increased CO_2 emissions from CW [36]. The authors of [37] analyse a large wastewater treatment plant (BOD_5 load 108,800 PE) in Italy for its carbon footprint. The biological stage uses activated sludge. Anaerobic treatment of sludge partially covers the energy costs of operating the treatment plant. The integrated assessment of the environmental sustainability of the wastewater treatment plant (WWTP) considered various sources of greenhouse gas emissions (N_2O and CO_2), wastewater, production, and transportation of natural gas, energy consumption, boiler, cogenerator, substrate, and endogenous decomposition processes. According to the developed methodology, the most serious sources of GHG were energy consumption, production and transportation of natural gas and N_2O emissions from wastewater. These sources were evaluated by the treatment plant management as the most relevant for taking measures to reduce the carbon footprint. The use of renewable energy can represent a significant contribution to the environmental sustainability of the WWTP. When assessing environmental vulnerability, it is important to distinguish between GHG emissions that can be captured and those which cannot be captured and thereby avoid the analysis of their origin. This results from the existence of available technologies that allow the capture/removal of produced CO_2, thereby preventing the accumulation of GHG in the atmosphere, regardless of their origin [37].

4. Sustainable Municipal Wastewater Treatment

Wastewater treatment processes and technologies ensure the removal of various micropollutants, and toxic substances. In addition, during wastewater treatment, pathogens are destroyed, biomethane is produced and usable bio substrates for agricultural production are produced. Improving the treatment efficiency should not only focus on conventional pollutants, but also on emerging pollutants (EPs). They include e.g., antibiotics that cause an increase in antibiotic resistance of human pathogenic bacteria in the aquatic environment [38].

Presented contributions [2] lead to a change in the strategy of wastewater management with an emphasis on minimizing energy consumption and restoring valuable resources. The findings of [3] indicates that wastewater treatment facilitates sustainable management of natural resources by improving clean water supplies and minimizing pressure on natural resources. Creates pathways for clean energy production and use, and significantly supports agriculture. By enabling the acquisition and reuse of valuable substances and purified wastewater, it significantly supports agricultural productivity, sustainable use, and protection of natural water resources.

Jetten et al. [39] discuss a new concept to significantly improve wastewater treatment practices by introducing new microbial processes. The concept considers the first stage with maximum sludge production. COD is removed as part of the sludge and thus the subsequent necessary aeration is reduced. Nitrogen is removed with minimal COD and energy requirements, while the remaining COD is used to produce energy in the form of methane (biogas). As a result of the digestion of sludge enriched with organic substances, a larger amount of methane is obtained for energy production. Nitrogen is only partially oxidized to nitrites, which are removed with a minimum of COD and energy since denitrification occurs with ammonium as the electron source [39].

A positive energy balance can be achieved by increasing biogas production, reducing aeration requirements, and regenerating nutrients. The problem of low concentrations of organic substances and nutrients in OV is solved e.g., segregation/thickening at the source or using membrane systems. By redirecting organic matter to the anaerobic reactor, the energy balance of the WWTP can be improved [40].

In the paper [41], a feasible municipal wastewater treatment process, using the upflow anaerobic sludge blanket (UASB) or the anaerobic baffled reactor (ABR) as an anaerobic pre-treatment system. Anaerobic pre-treated wastewater should be additionally treated in accordance with legislative requirements for their discharge. Given that the reed bed system is used for tertiary treatment, it could also be suitable for the additional treatment of anaerobically pretreated wastewater. Another cost-effective system of stabilization ponds with a suitable growth medium is also a potential system. Results obtained in pilot- and full-scale treatment plants showed that anaerobic processes represent a promising option for the pre-treatment of municipal wastewater in tropical and subtropical conditions at temperatures above 20°C [41].

The authors of the book [4] focus on solving the problems of wastewater treatment and disposal in developing countries. However, the presented concepts based on combined unit processes and operations are valid in suitable technologies even in developed countries. Sustainable treatment of municipal wastewater represents the application of basic engineering knowledge and procedures in the design and implementation of appropriate technologies for obtaining high-quality wastewater from treatment plants using simple, inexpensive, and easily controlled processes. Compared to conventional processes and technologies, they are therefore easy to control and usually require lower investments as well as operating costs. The authors provide the theoretical foundations, mathematical description, and parameters necessary for the design of unit processes, including some of their own innovations. They emphasize an innovative method of structured combined process design procedures used in developing countries that can be easily applied and followed by practicing engineers [4].

The authors of [42] deal with the transition of wastewater treatment plants towards a circular economy and energy sustainability in the context of the preparation and use of innovative filter materials. As the pollution of the planet increases, so does the need for effective air and water filtration. The period of the COVID-19 pandemic has confirmed the need for inexpensive, quick and in large quantities producible antiviral fiber materials. Antibacterial and antiviral fibers are very important for the protection of public health as well as in the medical environment. Biomaterials based on proteins and polysaccharides are promising alternatives to conventional synthetic materials used in filtration applications. They are inexpensive, occur in nature, and are easily produced with tailored properties. These tasks of efficient and ecological filtration of physical, chemical and biological pollutants can be fulfilled very well due to their properties, internal material properties, surface chemistry, and hierarchical morphology of biopolymer fibers. In addition, they are

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biodegradable, making them attractive as sustainable, biocompatible green filters. The paper provides an overview of various biopolymer materials based on proteins and polysaccharides, synthesis and production possibilities as well as successful filtration applications [42].

The authors of [43] designed and tested a new compact unit for sustainable municipal wastewater treatment for communities of 1,000 and 10,000 inhabitants. This integrated unit consisted of a combination of two UASB reactors, with a downdraft hanging non-woven reactor, an anaerobic baffled reactor (ABR), a chlorine unit and based on community populations of 1000 and 10,000 inhabitants. The operation was mainly focused on the sequencing of the bacterial community and the removal of parasites in this new combination of reactors. The results revealed structured microbial communities with the most widespread strain of proteobacteria. 40 to 66.7% parasite removal was achieved at 85.9, 90.7, 60.5, and 37% removal of COD, BOD, TSS, TKN, and TP, respectively. Based on the results, the authors conclude that this innovative integrated unit is technologically and economically promising for use in practice [43].

The authors of [44] deal with the potential of Municipal Wastewater Treatment Plants (WWTP) for a circular economy by implementing the 3R principles (reduction, reuse, and recycling). Although the primary function of a WWTP is to reduce wastewater (WW) pollution, the process generates several potentially valuable "by-products" including treated water, biogas, and sludge. Treated WW can be reused in various applications. Biogas can be used for electricity generation, heating, transportation, or even as a chemical raw material. Sludge can either be recycled into the soil as a conditioner or used through thermochemical/biochemical processing to obtain e.g., hydrocarbons, energy (e.g., heat and syngas), or valuable raw materials (e.g., phosphorus). The paper presents a five-layer framework for the quantitative assessment of the sustainable value of municipal WWTPs using the methods of life cycle assessment (LCA) and life cycle costing assessment (LCCA). Indicators of potential benefits for the benefit of interested parties and society are also used, for which they result from investments in municipal WWTPs (return on private investments and the ratio of environmental externalities to investments). Four prospective circular options (FCOs) were studied in a hypothetical case study for a WWTP with a capacity of 50,000 m^3/d. The sustainable value of the circular economy of the WWTP was evaluated for situations that include multiple possibilities of using treatment products. Individual FCOs differ mainly in the reuse of biogas (internal energy requirements of the WWTP, fuel for cooking or urban bus transport) and the method of sludge recycling (soil conditioner or electricity generation). The greatest sustainable value (lowest private costs and costs of environmental externalities, together with high incomes) goes to FCO with the reuse of treated wastewater in industry, the use of biogas as cooking fuel, and sludge as a soil conditioner [44].

5. Innovative and Novel Treatment Methods

Rapid urbanization substantially increases in drinking water consumption due to the development of urbanization and anthropogenic activities is accompanied by an adequate increase in the production of wastewater. Municipal wastewater is characterized by a dominant content of organic substances, nitrogen, and phosphorus. In municipalities, processes with the use of activated sludge are mainly used for the removal of organic substances. These systems are preferably also used for the biological removal of nitrogen and phosphorus. At the same time, organic pollution changes from a key pollution in conventional WWTPs to a raw material/source of carbon, which conditions the biological removal of these macronutrients in tertiary processes. This symbiosis of biological processes represents a significant streamlining of technological processes. However, the removal of macronutrients remains investment- and energy-intensive for municipal wastewater treatment plants.

The authors of [45] focus on clarification of the ability of photosynthetic microalgae to remove nitrogen and phosphorus from municipal wastewater and the subsequent possibility of using microalgae biomass as biofertilizer and biostimulant. Regeneration of nutrients from municipal wastewater by microalgae could potentially reduce energy consumption for nitrogen and phosphorus by 47% and 240%, respectively. Produced treated wastewater can be used for irrigation, while biomass from microalgae represents a potentially sustainable alternative source of nitrogen and phosphorus with a significant reduction in the consumption of inorganic fertilizers [45].

The anaerobic biological process takes place in the absence of oxygen. Microorganisms decompose organic substances into biogas (CH_4 and CO_2), reducing the amount of waste. It is an efficient and sustainable process that is used in wastewater treatment and reuse [46]. This process is environmentally friendly. It provides the production of renewable energy, the reduction of greenhouse gas emissions, and the production of digestate, which is rich in nutrients and has agricultural uses. The produced biogas can be used for electricity production, heating as well as raw material. It helps to minimize the negative environmental impacts associated with wastewater treatment and represents a promising technology for sustainable wastewater management. In addition to treating wastewater from various sources, it can be used in the processing of agricultural residues, food waste, and animal manure. The use of anaerobic processes has increased with the development and applications of high-speed reactors, which have significantly contributed to increasing the cost and environmental efficiency of this technique [46].

The authors of the paper [47] have developed a new process to produce the important and commonly used fertilizer ammonium nitrate. In the production of NH_4NO_3 from urine, a complete conversion of ammonium to nitrate was achieved in the first stage using comammox *Nitrospira*. In this process, the pH was maintained at 6 by the addition of base, which also provided sufficient alkalinity for complete nitrification. In the second scenario, NH_4NO_3 was produced directly by comammox *Nitropsira*, with half of the ammonium in the urine being transformed to nitrate without pH adjustment. The resulting product in this case contained ammonium and nitrates in a molar ratio of 1:1. The results showed that the comammox *Nitrospira* bacteria maintained their activity in the pH range from 4 to 8. However, the loss of activity occurred at pH 3 and 9. The results represent not only the application potential of the comammox *Nitrospira* bacteria when obtaining nitrogen from wastewater containing urine, he findings not only present an application potential of comammox *Nitrospira* in nitrogen recovery from urine wastewater but also report the survivability of comammox bacteria in acidic environments [47].

Intensification of nitrification and denitrification processes can be achieved by using a hybrid system with combined attached and suspended biomass [48]. A plastic block filling installed above the bubble aeration elements can be used as carriers of the attached microorganisms. Submersible modules made of plastic mesh or rotating discs can also be used. Microorganisms can be fixed to shaped plastic particles that move freely in the activation tank. It is advantageous to use microorganism carriers (e.g., plastic mesh or foam plastic), which allow the accumulation of biomass not only on the surface of the carrier, but also in the volume of the porous structure. It is obvious that in such system the degradation of biomass both on the surface and in the volume of carrier particles will significantly increase the amount of fixed biomass.

A two- to three-fold increase in biomass concentration in the system can be achieved in a single reactor by applying growth biomass carriers [49], which also corresponds to a proportional reduction in the sludge load in the reactor. An increase in the concentration of biomass in the reactor will not be reflected in an increase in the load on the secondary sedimentation tank. By using growth biomass carriers, two biocenoses with different sludge ages are cultivated in the system with activated sludge, which enables the simultaneous course of slower biological processes (nitrification, slowly decomposable organic substances) as well as faster processes (denitrification, and easily decomposable organic substances). Some types of carriers (e.g., foam plastic or plastic mesh) also allow a certain degree of so-called meso-segregation of microorganisms, thus creating conditions for simultaneous nitrification and denitrification processes in a single hybrid bioreactor.

Authors [50] measured a maximum oxygen concentration of 8 mg/L in a hybrid system using polyurethane cubes with an edge of 1.5 cm, while simultaneous denitrification was still taking place. It can be concluded that the application of the biomass carrier allows to reduce the volume of denitrification volume, and thereby also shortens the residence time of nitrifying bacteria outside aerobic environment conditions. In such hybrid systems, an improvement in the sedimentation and thickening properties of sludge is usually observed due to the fixation of fibrous microorganisms in the immobilized biomass.

Reduced nitrogen removal is economically attractive for wastewater treatment. However, the problem is achieving a stable suppression of nitrite-oxidizing bacteria (NOB) and simultaneously maintaining the activity of ammonia-oxidizing bacteria (AOB). The study [51] presents a new approach to achieve excellent partial nitrification (PN) in a membrane-aerated biofilm reactor (MABR) with acid-tolerant AOB *Candidatus nitrosoglobus*. The stability of the process was investigated over an operating period of 256 days. Nearly 100% washout of NOB was achieved in a MABR operated in the acidic pH range of 5.0 to 5.2 using in situ free nitric acid (FNA) of 1 mg N/L, with acid-tolerant AOB gradually enriched and becoming dominant. In addition to the potential application of reduced nitrogen removal from the main wastewater stream, MABR allows, due to the high rates of ammonia oxidation (about 2.4 kg N/(m^3d)), the prospect of intensification of the wastewater treatment process by significantly reducing the HRT in the bioreactor.

The work [52] deals with biological nitrogen removal (BNR) using new microorganisms that use new metabolic mechanisms for nitrogen removal. These include ammonia-oxidizing archaea (AOA), anaerobic ammonium oxidation bacteria ANAMMOX, complete ammonia oxidation bacteria (COMAMMOX), iron-reducing bacteria that cause anaerobic ammonium oxidation (FEAMMOX) and denitrifying anaerobic methane oxidation bacteria (DAMO). Compared to conventionally used nitrifying or denitrifying bacteria, these new microorganisms have better physico-chemical tolerance and are also more efficient in terms of greenhouse gas emissions. They represent potential microbial communities for new high-performance and energy-saving technologies for nitrogen removal from wastewater. During shortened nitrification (nitrification), significant investment and operating savings can be achieved by using the Anammox process. Ammonium ion-oxidizing nitrifying bacteria (AOB) oxidize 57% of input ammonium ions to nitrite, which saves approx. 50-60% of energy (oxygen consumption). Anammox microorganisms transform the remaining ammonia nitrogen and nitrogen gas [53]. Since anammox microorganisms belong to chemolithotrophic microorganisms, nitrogen is removed without the consumption of organic substrate. The production of excess sludge is approximately 80% less in this process. In the anammox process, is transformed up to 13% of the input nitrogen into nitrates, which are partly heterotrophically denitrified in the process. heterotrophic microorganisms. Anammox technology is highly efficient. Suggested load values can be 0.35–2.3 $kg_N/(m^3/d)$ [54], in some cases up to 10 $kg_N/(m^3/d)$ [55].

In the work [56], an overview of nitrogen removal methods from wastewater is given. Simultaneous nitrification-denitrification (SND) using oxic and anoxic conditions and appropriate microbial populations is suitable for the biological removal of nitrogen from municipal wastewater. Combining anammox with denitrification has the potential to increase nitrogen removal rates and reduce energy consumption. Bioreactors using activated sludge are resistant to changes in COD/N ratios and low C/N ratios. Biofilm bioreactors show greater stability, better biomass separation properties, and increased cleaning efficiency. SND studies show the overall nitrogen removal efficiency in SND systems is ≥90%. Anammox denitrification reaches 77% efficiency. The authors emphasize the importance of microbial processes in nitrogen removal. They consider SND and the anammox process as potential methods with significant nitrogen elimination. In processes with the combined use of microalgae bacteria, the need for oxygen and carbon is reduced, thereby increasing the efficiency of nitrogen removal. The efficiency of biofilm processes can be increased by using suitable reactor technology, e.g., fluidized bed bioreactors. Suspended growth bioreactors are increasingly recognized as highly promising nitrogen removal systems due to their simple design and cost-effectiveness. Bioreactors demonstrate their adaptability by efficiently accommodating a range of microbial activities such as anoxic and aerobic phases, anammox, and simultaneous nitrification-denitrification (SND). Remarkable findings reveal a strong tendency towards low COD/N ratios, highlighting the potential of these bioreactors to adapt to different wastewater conditions. The inclusion of comammox bacteria in the UASB bioreactor with dominant anammox has a favourable effect on the elimination of total inorganic nitrogen.

The sustainability of wastewater treatment is also linked to efforts to restore the resources contained in them (phosphorus, nitrogen, organic fertilizers, water, and methane). In addition to the energetic use of organic matter, the use to produce more valuable products is being reassessed, e.g., biodegradable polyhydroxyalkanoates (PHA), which could be used as a substitute for common plastics. The production of PHA by means of mixed microbial cultures (MMC) is not limited to the use of organic compounds not only from municipal but also from industrial wastewater [57,58].

A new Anaerobic-Anoxic-Oxic/Sequential Batch Phosphorus Sidestream Recovery (MO-SBSPR) process has been developed for phosphorus (P) regeneration and nutrient removal from municipal wastewater. In work [59], a process operation strategy based on a P mass balance was proposed. To reduce the effect of P regeneration on the P content in the activated sludge and to maintain stable process operation, the level of P regeneration was linked to the sludge retention time (SRT). During stable operation of the AAO-SBSPR process, up to 65% of the inflowing P was recovered with a phosphate removal efficiency of 99.1%. Both P recovery and prolonged SRT had a limited effect on the rate of P release and uptake by polyphosphate-accumulating organisms (PAOs). The relative abundance of *Accumulibacter* increased, while the SRT was prolonged at a high recovery rate of P. In addition, significant nitrogen removal and P uptake were also observed. The ratio of anoxic P uptake to total P uptake in the whole process increased from 41.7% in the AAO process to 77.5% in the AAO-SBSPR process. In this process, the efficiency of total nitrogen removal also increased from 71.9% to 80.4%. In the P regeneration process, because of the increase in the SRT value, the nitrification process was also supported and sludge production decreased. Overall, the results show that the AAO-SBSPR process, including the proposed operating one, provides a promising alternative for the regeneration of P from municipal wastewater.

The authors of [60] opened a discussion about the future process of municipal wastewater treatment. The conventional process using activated sludge (CAS) has been used in technological practice for more than 100 years. During that period, it underwent extensive development in terms of target pollution, reactor and technological layout, mathematical modeling, optimization, and control [61]. The authors of this work and other supporting articles state that with the increasing demands for energy consumption, carbon emissions reduction, and the quality of discharged wastewater, it appears that the CAS process, even with further optimization, cannot cope with the current and future situation [62,63]. For example, the biological oxidation of organic matter and ammonia in wastewater requires a significant amount of energy, which is accompanied by GHG emissions. The wastewater treatment technology strategy should shift from the current single function of removal to a multi-functional synergistic recovery of treated wastewater, resources, energy, and carbon neutrality to achieve maximum environmental and economic sustainability. The authors' effort is to use the given data and their analysis to clarify that the process of using microalgal bacterial granular sludge could be promising for achieving the regeneration of municipal wastewater, including energy production, recovery of material resources, and reduction of the carbon footprint.

Stable and high-performance conditions for the biological removal of macronutrients are created by recently developed advanced BNR technologies. Compared to conventional BNR technologies, new technologies differ mainly in improving efficiency, and saving operating costs and energy [64,65]. They include e.g., simultaneous nitrification/denitrification (SND), bioaugmentation batch treatment (BABE), anaerobic oxidation of ammonium (Anammox), denitrifying phosphorus removal, single reactor removal of ammonia over nitrites (SHARON) [66–69].

A new technology has been developed for the treatment of wastewater with a high nitrogen content, which uses the process of anaerobic ammonium oxidation (ANAMMOX). This process is performed by anaerobic ammonia-oxidizing bacteria (AOB), which oxidize half of the ammonia to nitrite. ANAMMOX bacteria (*Candidatus Brocadia fulgida*) use nitrogen nitrite as the final electron acceptor to oxidize residual ammonia to N_2 [70]. In 2014, the authors of [71] from Delft University published on simultaneous partial nitritation and the ANAMMOX process in a suspended biomass system.

Advanced biological nitrogen removal processes (BNR), e.g., nitritation-denitritation and ANAMMOX, therefore, compared to current BNR processes, show a significant reduction in the need for oxygen and organic substrate. The ANAMMOX process further reduces the oxygen demand by 60% without the need for an organic substrate [72].

The authors [73] deal with the mechanisms, advantages, disadvantages, and limitations of currently used and advanced processes and technologies for removing N and P from municipal wastewater (WW). The advantage of simultaneous nitrification and denitrification (SND) is its simplicity of operation and management, low energy costs, economy, and efficiency. Simultaneous nitrification, denitrification, and phosphorus removal (SNDPR), which is mediated by the integration of denitrifying phosphorus-accumulating DPAO organisms into the SND process, is also a promising process. In the literature [74–78], one can find information about some facultative denitrifiers capable of accumulating phosphorus under anoxic/aerobic conditions, i.e., j. without the need to alternate between anaerobic and aerobic/anoxic conditions. These bacteria can use nitrate and/or nitrite as the final electron acceptor instead of oxygen. This process of simultaneous nitrogen and phosphorus removal is also known as denitrification phosphorus removal [76]. Both PAO and DPAO possess enzymes for aerobic metabolism. However, PAOs do not have enzymes that allow the use of nitrates as the final electron acceptor. Only DPAOs can denitrify phosphorus uptake [79]. Using the enzyme polyphosphate kinase (PPK), they can synthesize polyphosphate under aerobic or anoxic conditions, i.e., without alternating anaerobic and aerobic/anoxic conditions [80]. The process of denitrification of absorbed phosphorus provides energy savings, lower carbon source requirements, and less sludge production compared to conventional EBPR [81]. In the case of DPAO, the carbon source is the same for both denitrification and phosphorus removal. This results in approximately 50% savings in COD requirements [64]. Due to the efficient use of limited carbon sources in municipal wastewater, this process can also be used in WW treatment with a slightly low carbon-to-nitrogen ratio [77]. A combination of archaeal ammonium and anammox-modified denitrification processes, which do not require the addition of external carbon, is recommended for the consolidation of nitrogen removal and phosphorus recovery from wastewater with a low carbon/nitrogen content [73].

Heterotrophic nitrification and aerobic denitrification (HNAD) eliminate the shortcomings of biological nitrogen removal systems, in which the individual processes of nitrification and denitrification are implemented due to the different specifics of the individual processes and the microorganisms used (the speed of autotrophic bacteria, their high sensitivity to organic loads, the influence of dissolved oxygen on denitrification) discretely in two separate bioreactors. Such a solution is associated with high costs [82]. The results of recent research revealed the existence of some heterotrophic nitrifiers capable of nitrifying using organic carbon [83–85]. At the same time, many of them can denitrify the products of their nitrification, i.e., nitrates and/or nitrites, to N_2 [86]. Thus, they can simultaneously use dissolved oxygen and nitrates and thus allow nitrification and denitrification to take place in one reactor under oxic conditions. Thus, they use nitrates/nitrites as the final electron acceptor and this process is referred to as the SND process [87]. SND implemented is cost-effective (22–40% reduction in carbon consumption and approximately 30% reduction in sludge production) [74]. The implementation of both nitrogen removal processes in one reactor is significantly simpler. Higher growth rates of microorganisms and their ability to use organic carbon as an energy source, as well as the ability to use the products of the nitrification process as reactants for denitrification, are reflected in the higher efficiency of this reactor. Reduced intensity of aeration and minimization of recirculation are reflected in lower energy consumption. Alkalinity produced during denitrification is partially balanced by acidity produced during nitrification [88], so pH control requirements are minimal. The variety of substrates and products enables the expansion of the application possibilities of heterotrophic nitrification [89]. The HNAD technology enables to treat wastewater with a low C/N ratio as well as the lower availability of CO_2 for autotrophs [90].

SND technology overcame the limitations of commonly used nitrogen removal technologies and provides a progressive technology for this biological process [91–93]. However, this technology makes it possible to integrate N and P removal processes and phosphorus recovery as well. As previously mentioned, the denitrification phosphorus removal process can simultaneously remove nitrogen and phosphorus under aerobic or anoxic conditions in a single reactor without alternating anaerobic/anoxic/oxic conditions [94]. It allows the incorporation of DPAO into the SND process, thus

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developing a simultaneous nitrification, denitrification, and phosphorus removal (SNDPR) reaction system. Compared to the conventional EBPR mechanism of biomass phosphorus enrichment, in the case of SNDPR, there is liquid phase phosphorus enrichment mediated by DPAO. Phosphorus can be easily recovered from the enriched liquid phase by induced crystallization. This procedure is considerably simpler compared to the recovery of phosphorus in the EBPR system [95] and is certainly a more ecological and efficient approach.

The application of an energy- and resource-efficient alternative to mainstream anammox would also be promising. A fundamental problem remains the selective enrichment of AOB and the simultaneous inhibition of NOB due to the continuous supply of nitrites [69]. Ammonia-oxidizing archaea (AOA) with high efficiency of its oxidation under oxygen limitation could be potentially more suitable microorganisms for nitrite supply and the possibility of connection with the anammox mainstream [96]. The simultaneous removal of N and P can effectively utilize even the limited carbon content of WW with a slightly low carbon-to-nitrogen ratio [97].

6. Sustainable Techniques for Removal of MPs

Emissions of harmful substances are a permanent concern of the European Union and a number of documents are focused on this problem (Water Framework Directive [98] defines the framework of EU water policy, Decisions [99–101], Stockholm Conventions, [102,103], classifying priority/priority hazardous substances and establishing the first watch list (“watch list”) which contains 10 substances/groups of substances including three antibiotics, natural hormones, some pesticides, a UV filter, and an antioxidant commonly used as food additive [104]. In accordance with the Water Framework Directive, environmental quality standards (EQS) have been established for 45 priority substances including micropollutants (MPs).

The most serious problems considering health and environmental protection are, yet to be resolved, environmental burdens [105] of persistent substances (e.g., polychlorinated biphenyls or organochlorine pesticides). Therefore, new technologies are proposed, such as advanced oxidation processes (AOPs) [106], employing ozone, which draws more attention mainly after their recent applications in urban WWTPs in Switzerland [107].

Micropollutants (MP) are characterized by significant negative effects on ecosystems and humans even in low concentrations (μg/L to ng/L). These effects include acute and chronic toxicity, bioaccumulation, and bioconcentration in food chains, as well as genotoxicity, or endocrine effects [108]. They are found in the aquatic environment and have a negative impact on plants, animals, and humans [104]. MPs and emerging pollutants (EPs) from the groups of pesticides, pharmaceuticals, personal care products, and industrial chemicals have adverse effects on the balance of environmental components. Authors [106] introduced an analytical method for trace quantification of 37 micropollutants, including priority substances [100], substances from the watch list [101], and contaminants of emerging concern: pesticides, pharmaceuticals, and their metabolites, estrogens, and one industrial compound. An important source of MPs in the environment is combustion of solid waste???, which can produce polychlorinated dibenzodioxins (PCDDs) and some polyaromatic hydrocarbons (PAHs).

The problem of MPs is not only their diversity, complex structure, estrogenic, carcinogenic, and toxic effects, and low or no biodegradability, but also their ability to bioaccumulate and persist in the environment rendering their removal from complex matrices by currently used wastewater treatment procedures and technologies insufficient and creating new challenges for the scientific community [106,109].

The removal of MPs is not an easy task from the engineering and technological point of view. Their harmful effects are manifested even at very low concentrations, and the situation is complicated by large flows of treated water, which increases the operating and investment costs. It is known that the most significant point sources of micropollutant emissions are municipal wastewater treatment plants [110–112], where only about half of the MPs present are removed, either by their degradation or by sorption into sludge. Due to their serious negative effects on the environment, low concentrations, and, in many cases, complex chemical structure, the issue of MPs removal represents

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an urgent and current challenge in the treatment research, the investigation of their effects on the aquatic environment, and their penetration into groundwater [109].

Current practice in treating WWs does not sufficiently solve the problem of priority/priority hazardous substances and MPs neither in the water and gas phase nor when managing waste sludge. According to the literature and our experience, processes using ozone are the most promising in this area. Further research should focus on reducing emissions of hazardous substances present in sludge, water discharged from WWTPs, and in the gas phase where water treatment products may be present.

Deblonde et al. [113] found removal efficiencies of phthalates, antibiotics, and bisphenol A above 90%, arround 50% and 71%, respectively. In their study, they have monitored concentrations of 50 pharmaceutical compounds, six phthalates, and bisphenol A at the inflow and outflow of a WWTP. Singh et al. [114] published results from semi-operational ozonation after secondary treatment of municipal WW for 41 target EPs at two ozone doses (0.46 and 0.72 mg O_3/mg DOC) and found removal efficiency of more than 80% at both ozone doses for seven EPs (bisphenol A, carbamazepine, diclofenac, indomethacin, lincomycin, sulfamethoxazole and trimethoprim).

MPs and EPs can accumulate and biosorb onto hydrophobic organic substances of activated sludge, and therefore the disposal of contaminated sludge is also an environmental problem. One of the current trends in sludge management is the research of integrated biological and chemical processes minimizing the production of excess sludge and carrying out simultaneous transformation/degradation of MPs adsorbed on activated sludge [115]. Several studies on the treatment of excess sludge indicate ozonation as one of the simplest and fastest modern emerging technologies for MPs removal and prevention of their subsequent release into the environment [109,111,116].

Ozone is a strong oxidizing agent capable of cell lysis and disinfection, reduction of suspended solids, and increase of dissolved COD [117,118]. It selectively reacts with molecules with unsaturated bonds such as phenols and olefins. Ozone can also react through the radical mechanism, as secondary $^{\bullet}OH$ radicals are formed because of its decomposition in water, contributing thus to the higher efficiency of MPS removal at low doses of ozone [119]. Moreover, transformation products formed by direct reaction with ozone or indirect reaction with $^{\bullet}OH$ radicals are less biologically active than the original compounds [120].

Ozonation of excess sludge was studied in several papers. Authors [110,111,121] showed increased removal efficiency for a wide range of monitored substances, increased biogas production, reduced sludge production, and concluded that by combining several technologies, the efficiency of substance removals can be increased.

The advantages of using ozonation of water and sludge as well as the use of integrated systems, e.g., a recirculating reactor or a fluidized bed reactor with a tubular reactor for homogeneous and heterogeneous reactions in the gas phase for MPs and EPs emissions removal, are thus obvious. Ozonation can be applied in MPs degradation in the gas phase stripped during purification in a tubular reactor [122]. An integrated system employing the generated ozone in WW and the residuum of reactions of volatile substances with unreacted ozone in a tubular reactor in a homogeneous or heterogeneous reaction mode is considered effective.

Current practice in WW treatment does not sufficiently solve the problem of priority/priority hazardous substances and MPs/EPs. Therefore, it is important to focus research activities on harmful substances present in water discharged from WWTPs, on processes reducing the production of excess sludge and its processing, and on reducing volatile components in the gas phase. Processes using O_3 seem to be the most promising ones in this area.

Research on processes using O_3 in WW treatment considers several aspects. One of them is the use of O_3 in the removal of MPs [113,115,123], which is also characteristic of existing implementations in practice, in combinations with other reactants by transformation to AOP with a characteristic radical mechanism [124], its application in treatment [29] or after biological treatment [114,125,126] in combination with other processes (sand filtration, adsorption on AC) [108,127,128], in MPs removal from sludge [111], reduction of excess sludge production [110,115] or its use as a renewable source of organic C for biological removal of macronutrients [117], in increasing biogas production and MPs removal from anaerobic sludge [129] or from separation processes concentrates, as well as in the removal of volatile substances [122].

Municipal wastewater treatment plants (WWTP) are usually not designed to remove hazardous emerging contaminants (EC). Secondary processes (e.g., conventional process using activated sludge) and tertiary processes (e.g., disinfection and filtration) are not very effective in removing EC from the sewage supplied to the WWTP. The authors of [130] investigated advanced methods that could be used for CE removal, including consolidated processes (adsorption with activated carbon (AC), ozonation, and membranes) and new processes (advanced oxidation processes (AOP)). Members of the international NEREUS COST Action ES1403 group for the best available technologies for advanced municipal wastewater treatment participated in the solution. This work evaluates the available scientific articles on these processes with the aim of analyzing their EC removal efficiency, advantages and disadvantages, possible limitations and applications, mid- to long-term perspectives of applications, and technical and economic comparison of processes and technologies. Prospective methods of heterogeneous photo-Fenton reaction, photocatalytic ozonation, photocatalytic membrane processes, electrochemical oxidation, and hybrid processes for EC removal were investigated, but due to technological limitations and costs, they were not applied. However, they can be included in the long-term perspective of the EC removal method. ECs can be effectively removed from municipal WW using consolidated advanced methods of PAC/GAC adsorption, ozonation, nanofiltration, or reverse osmosis membranes. Several facilities using AC adsorption and ozonation have recently been implemented at full scale in a cost-effective manner in Germany and Switzerland. The most expensive processes include nanofiltration/reverse osmosis [130].

7. Sustainable Sludge Management

In recent years, developments in sludge management have taken a turn in a completely different direction. The use of sludge as fertilizer in agriculture and landfilling was for a long time the most common sludge application, but today sludge is in terms of sustainability presented as a new energy and material resource. Despite sludge presenting only a few percent of the volume of the processed wastewater volume, its treatment costs represent up to 50 % of the WWTP operating costs [131]. To contribute to more sustainable sludge management, the economic, social, and environmental aspects of all the sludge treatment processes need to be considered.

The composition of sewage sludge changes significantly during the treatment process and can vary widely between different wastewater treatment plants. In general, untreated (raw) sewage sludge contains 2.0% to 8.0% total solids (TS), with volatile solids (VS) constituting 60% to 80% TS. It also contains various components such as fat and fats, proteins, nitrogen, phosphorus, potassium, cellulose, iron, silica, alkalinity (measured in mg/L as $CaCO_3$), and organic acids (measured in mg/L as Hac) [132,133].

The primary problem with sludge is the presence of all these compounds combined in one mixture. Compounds containing organic carbon, phosphorus, and nitrogen are often considered valuable, as are many inorganic compounds. Sustainable cleaning focuses on the recovery and reuse of these valuable components while minimizing the potential negative impacts of sewage sludge on the environment and human health [132].

A sludge treatment is a combination of different treatment processes. It can be divided into 3 main phases: pre-treatment, main treatment, and final treatment (end-use). The main purpose of pre-treatment is to enhance the following processes. Mechanical (high pressure, ultrasound), thermal (thermal hydrolysis), chemical (ozonation), and biological (aerobic and anaerobic processes) methods are most used for the improvement of sludge stabilization, biodegradability, and biogas production in the next phase [134].

The advantage of aerobic processing is also the smaller production of sludge, which significantly reduces the operating costs of the WWTP. For WWTPs with a smaller organic load, e.g., ozonation, which accelerates the hydrolysis/desegregation of suspended substances and reduces the overall costs of wastewater treatment [135].

In the review conducted by Carrere et al. [136] a comparison of different pre-treatment methods was made. It was reported that pre-treatment increased the biogas production from 15 to 90%. A comparison of the efficiency of methods showed the thermal methods were the most effective in terms of increased biogas production, while the energy input was higher than at the other methods.

The second phase of sludge treatment presents anaerobic digestion that converts the degradable organic compounds in sludge to biogas (a mixture of methane, carbon dioxide, and other gases). Biogas production depends on the type of pre-treatment method and temperature during the anaerobic digestion. The process of anaerobic digestion is divided into 4 stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. All stages occur in the same digestor. Anaerobic digestion stabilises and reduces the amount of pathogens in the sludge. The production of biogas from sludge is crucial in the field of renewable energy sources, because it can be used at the same time as a source of heat, and electricity production [137,138]. According to past studies, the total calorific value of biogas as an anaerobic digestion product is approximately from 28 to 39 MJ/Nm^3 [139,140].

After the anaerobic digestion as the final stage, thermal processes are used to reduce the volume and weight of the sludge and to destroy the pathogens and toxic compounds. Thermal processes include combustion and other thermal or thermo-chemical processes such as pyrolysis, gasification, liquefacation, and wet oxidation [141].

Before thermal processes, a reduction of water content in anaerobically digested sludge is crucial. Water content is reduced by dewatering (chemical conditioning and mechanical dewatering) and drying. Drying is crucial when combustion, pyrolysis, or gasification are used as final thermal treatment because the dry solid content in sludge needs to be >85% [142]. Crine and Leonard [143] reported on performances and energy demand of sludge dewatering and drying. To achieve the dry solid content with mechanical dewatering in digested sludge <25% the energy input of up to 10 kWh/t water is needed, while for >95% of dry solid content with drying the energy demand is approximately 1000 kWh/ t water. According to this, the energy demand for the drying process is around 100 times higher than the mechanical dewatering.

Combustion is an oxidation process at high temperatures to destroy toxic compounds and convert the sludge into water, carbon dioxide, and heat. Additionally, the result of sludge combustion is the presence of toxic compounds from the sludge in flue gas (dioxins, furans, nitrogen oxides, sulfur dioxide, etc. [144,145].

Sludge from WWTP can be also used in cement kilns for cement production as partial coal or coke replacement in the kiln. Inside the cement kiln, the temperatures are above 1400 °C and consequently almost all organic compounds in the sludge are destroyed. Also, the recovered heat from the kiln can be used for the sludge drying process [146,147].

Pyrolysis and gasification are the two most promising final sludge treatments. The most wanted product of pyrolysis is bio-oil due to its high calorific value of >30 MJ/kg and the possibility of using it as fuel (biofuel) [148,149]. Compared to pyrolysis, gasification is a process like pyrolysis, but it is conducted at higher temperatures and in the presence of an oxygen supply and more gaseous products (syngas) are being produced. The syngas can be then used for further hydrogen production or as a natural gas replacement due to its calorific value of up to 6 MJ/Nm^3 [150,141]).

Besides bio-oil and syngas, biochar is produced as a solid product of pyrolysis or gasification. Several studies presented multiple options of char use as an effective soil conditioner and as a substitute for various materials in different fields. One of the most promising biochar applications is its use in the construction sector, especially as a partial cement replacement in concrete. Because the cement industry is known as one of the largest sources of carbon dioxide emissions, more sustainable options are being researched. It was confirmed that biochar use in cementitious composites has a great potential to successfully replace cement due to an improvement of material properties and contribution to climate change mitigation. Furthermore, the direct capture of carbon dioxide in biochar structure was also confirmed [151,152].

Ibarrola et al. [153] investigated carbon abatements of different biochar production processes (slow pyrolysis, fast pyrolysis, gasification) from sewage and paper sludge. It was found that both

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had similar net carbon abatement for slow pyrolysis treatment which was around 0.8 kg of CO_2-eq/kg of biochar, while fast pyrolysis and gasification treatment net carbon abatements were lower (around 0.5 kg of CO_2-eq/kg of biochar). Some predictions were also made on energy generation during biochar production processes. Gasification appeared to be most effective, and considering the feedstock type, the one with the low water content is the most appropriate. A comparison of the amount of generated electricity per tonne of feedstock revealed that paper and sewage sludge would achieve the lowest amount of electricity per tonne of feedstock (around 0.7), while other feedstock (waste wood, cardboard, and others with lower water content) would achieve 15-80% higher amounts of generated electricity. Past studies reported that sludge treatment and final disposal treatments in WWTP can contribute up to 50% of GHG in WW treatment systems [154,155].

Some of the processes have almost no possibility of improvement. However, with a proper combination with other treatment processes the sustainability of the sludge treatment process could still be improved. Furthermore, when determining the most sustainable method for sludge treatment, the local environment (conditions, transport) needs to be considered.

Pippo et al. [156] investigated which sludge treatment (anaerobic digestion, composting, incineration) process had the lowest GHG emissions due to the local environment in Finland (cold weather, long-distance transport). It was found that anaerobic digestion resulted in the lowest amount of GHG emissions, while the composting (biological treatment) had the highest amount of GHG emissions regardless of the transportation and weather conditions.

According to the costs, energy demand, and environmental aspects (GHG emissions) of sludge treatment processes, anaerobic digestion presents the most appropriate main treatment. However, the pre-treatment is most efficient using thermal treatments, while in terms of energy consumption and GHG emissions (heat and electricity production), there is a concern. Also, pyrolysis and gasification appeared to be the most promising final thermal treatment, but not without dewatering and the drying of the wet sludge due to low dry solid content, which is the most energy-consuming process in the sludge treatment. This could be improved by using heat, liquid (bio-oil), and gaseous products from pyrolysis, gasification, and biogas from anaerobic digestion for energy (heat and electricity) production. Also, it could cover the need for heat in pre-treatment to increase the efficiency of sludge management in terms of energy recovery. To add, the disposal of the products of the final treatment was found to be very promising as well, especially biochar application in concrete as cement replacement in terms of carbon capture and sequestration.

7.1. Sewage Sludge Disposal

Primary strategies for the sustainable management of sewage sludge include material recovery, energy recovery, and other methods.

Matter Recovery (Sewage-to-Matter) includes the direct use of sewage sludge in agriculture as fertilizer and rehabilitation of degraded or devastated land.

Energy recovery (wastewater to energy) includes incineration and alternative thermal methods such as pyrolysis, quasi-pyrolysis, and gasification. It also includes co-incineration in cement plants and the conversion of chemical energy in wastewater into usable forms to meet renewable energy requirements [157]. Various technologies are used to transform excess sewage sludge into energy, thus addressing the environmental risks associated with land use and supporting global renewable energy needs.

7.2. Sewage Sludge Disposal

Pyrolysis is characterized by a lack or absence of oxygen and high temperature. During the pyrolysis process of waste biomass, the highest temperatures range between 300 °C and 800 °C. Besides the pyrolysis process, torrefaction and gasification are also used for biomass recovery. During the gasification of waste biomass, higher temperatures (≥ 800 °C) are reached, and the entire process takes place in the presence of oxygen, which results in lower amounts of char produced compared to pyrolysis. Three products of pyrolysis are syngas, bio-oil, and char. Pyrolysis can be divided into 3 phases. The first phase begins with the gradual heating of the biomass inside the reactor and then moisture evaporation (drying). In the second phase, when the temperature in the reactor reaches 150 °C various organic components begin to decompose, and the evaporation of various gases (hydrogen, carbon dioxide, carbon monoxide, methane) begins. The biochar formation process also begins in the second phase. The most important process of pyrolysis of biomass takes place throughout the second phase until the maximum temperature is reached, after which the temperature in the reactor starts to drop. As the temperature drops, the pyrolysis process moves into the third phase, where small amounts of gases and biochar are still produced, and the entire system gradually cools down. In the last 20 years, biochar production has become the subject of many studies. The results have shown that it is applicable in many areas, such as reducing climate change, waste management, agriculture, construction, and the energy sector. Not only the extraction process but also the use of biochar itself shows its positive effects in various areas, such as the use of biochar in wastewater treatment processes, where activated biochar is most usually applied.

Initially, anaerobic digestion (AD) was viewed as a technically advanced and cost-efficient process that changes sludge into biogas, with the primary goal being the elimination of pathogenic bacteria [159]. WWTPs with a significant need for electricity up to 0.78 kWh per m^3 of treated wastewater can use the generated biogas for their own energy needs [160].

To increase the efficiency and yield of biogas, it is recommended to add other components in co-digestion. Grosser [161] used grease trap sludge and the organic fraction of municipal waste as a co-substrate, where the methane yield was twice that of sewage sludge alone. The results also showed that the optimal mixture ratio of 30% grease trap sludge (GTS), 30% organic fraction of municipal wastewater and 40% sewage sludge based on vs showed effective co-fermentation and a higher increase in methane production [161].

Maragkaki et al. [162] also observed a significant increase in methane production, where mixtures of dried food waste, wastewater from cheese whey and olive mill were used as co-substrates [162]. Co-digestion of sewage sludge can be considered as a method of handling various organic wastes. However, it does not serve as a final solution for sludge disposal as it creates another by-product known as digested sludge (digestate). This digestate still contains significant amounts of nutrients and contaminants that require further processing. Research has shown that digestates can potentially replace or limit the use of mineral fertilizers in agricultural crop production due to their richness in plant-available nutrients such as ammonium, phosphate, and potassium [163]. However, the use of digestate as a biofertilizer on land is only possible if it meets the standards set by the relevant regulations, which are usually governed by soil protection laws, fertilizer regulations, or waste management legislation. If it does not meet these criteria, alternative disposal methods must be explored.

8. Energy Optimisation of Municipal Wastewater Treatment Systems

Treatment of wastewater is necessary to prevent pollution from being discharged into water courses. It can also provide water that is sufficiently clean for reuse in certain contexts, which can be particularly useful in areas suffering from water stress. However, the sector of urban wastewater removal and treatment is responsible for 0.8% of the total electricity consumption and about 0.86% of all greenhouse gas emissions in the entire EU (D'Antoni, 2016). Almost a third of these emissions could be prevented by improving the treatment process, better use of sewage sludge, and increasing energy efficiency, as well as a higher rate of use of renewable resource technologies. On the other hand, new treatment methods are required to be included in the treatment system to address the removal of micropollutants due to the new European directive expected [1]. Due to the high energy demands of WWTPs, treated water is often more expensive than drinking water and its reuse and recycling are still very limited.

For the assessment of electricity consumption in the wastewater treatment processes, a comparative method – benchmarking - is used, as a very useful tool for evaluating the energy efficiency of wastewater treatment plants. It was developed at an international level and enables the evaluation of the energy efficiency of water treatment plants based on data from various researchers in Europe and around the world. The research covers WWTPs of different sizes, and various

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technological processes of wastewater treatment and provides data on target and normal values of process indicators. Optimization of the consumption of electricity means lower operating costs thus it is essential.

8.1. Overview of Energy Consumption of WWTPs in Europe

Treatment plants use electricity and heat to carry out their processes and are one of the largest consumers of electricity in the energy system. In Slovenia, electricity represents about 20% of the total energy consumption. In 2016, the number of WWTPs was around 480 and they represent roughly 0.3% of electricity consumption. Estimation is based on electricity consumption in Slovenia in 2015 and the number of population equivalents (PE) of all 480 WWTPs. The average consumption of specific electricity is based on data for average European WWTPs consumption. The Enerwater study states that Italy consumes 1% of electricity for WWTPs, Spain 2-3% and USA 4%. Across the EU, there are around 16,000 wastewater treatment plants (WWTPs). WWTPs in the EU consume around 10,000 GWh per year. The volume of wastewater being treated in the EU is increasing by around 7% each year, creating an additional environmental burden. This energy in Europe mainly originated from fossil fuels. At the same time, energy consumption from WWTPs creates emissions of more than 27 million tonnes per year of CO_2. In Spain alone, WWTPs consume 2,213 GWh per year resulting in the emission of more than 6 million tonnes/year of CO_2 [164].

Larger treatment plants (PE) use electricity more efficiently than smaller ones. The largest consumers of electricity in managing the technological process of wastewater treatment are air blowers in the aerobic stage, pumping stations intended to transport the wastewater and mixers in various types of reactors. Aqualitrans Project [165] identified the main energy consumers: the aeration equipment associated with biological treatment (58%), inlet pumping (9%), deodorization (8%), and sludge treatment equipment (6%).

The overall wastewater treatment plant (WWTP) electricity use in Europe of plants with more than 2,000 PE was estimated to be at least 24,747 GWh per year and this represents about 0.8% of the electricity generation in the EU-28 [166]. Small plants (less than 50,000 PE) represent almost 90% of the total electricity consumption, but process only 31% of the PE, while they absorb 42% of electricity use. Plants from mid to very large size (10% of the plants), process the majority of the PE (70%) and use 58% of the total electricity. If all plants that use more than the current average were optimized to achieve the average electricity consumption, the savings would be more than 5,500 GWh per year. With highly stringent targets of efficiency improvement, savings of about 13,500 GWh per year could be expected [166]. In a study of the operating costs of wastewater treatment plants in Austria, they found that 56 % of all operating costs depend on the load on the treatment plant. Energy accounts for 18-45% of all operating costs, of which 54% is dedicated to aeration, and of course, it all depends on the load on the treatment plant itself [167]. If the aeration process in the aerobic system is optimized, the reduction of all operating costs could be between 4 and 11%. Other important energy consumers are pumping stations, which account for about 12% of the total energy used, sludge treatment processes, these processes use about 15% of the total energy used, mixing uses 7% of the total energy used, and approximately 4% of the total energy used these are pumping stations intended for sludge recycle [167]. Chemicals (precipitating agents, etc...) represent somewhere between 14% and 32% of all operating costs, which again depends on the load on the treatment plant, and around 18% of all operating costs are the costs arising from the generation of waste and its removal. In the case of the phosphorus precipitation process, this affects two different groups of operating costs, the costs of applied chemicals and the costs of water treatment.

8.2. Benchmarking od WWTPs Energy Efficiency

Benchmarking can be an efficient tool to compare WWTPs performance in terms of energy sustainability. This is the tool with which we measure the WWTPs performance against the best in the same or similar system. Improvements based on this approach take place in five steps:

1. preparations and planning,
2. data collection,

3. determination of normal and target values of process indicators,
4. analysis; and
5. realization (optimization of processes).

The process of determining energy efficiency consists of two parts [168]:

1. Review of electricity consumption data and processing of only these:

- rough estimate of electricity consumption,
- use of process indicators that can be easily determined,
- evaluation of process indicators in a certain period,
- identification of gaps and errors and
- formulation of possible measures.

The aim of the analysis is to improve the energy efficiency of the municipal sewage treatment plant. Compared to the first step, this step goes into more detail:

- determination of the actual consumption of electricity,
- determination of the sum of the different actual electricity consumption of each part of the equipment,
- determination of ideal values (theoretical calculations), electricity consumption according to the equipment used,
- assessment of the current situation and determination of measures for improvement,
- taking economic aspects into account, electricity savings are calculated, and the efficiency of the municipal treatment plant is improved and
- determine the priorities of work tasks for improvement measures.

One of the basic requirements of benchmarking is the comparability of the inventory that should be analysed. Basic conditions for the comparability of data itself should be considered. In the case of WWTPs, these conditions are hydraulic, topographical, geographical, geological, and urban factors in the micro-location. To evaluate the energy efficiency of conventional municipal WWTPs, the following process indicators within the framework of the benchmarking are usually used [167]:

- Specific electricity consumption per PE [kWh/PE/year]
- Specific electricity production per PE [kWh/PE/year]
- Electricity consumption rate for aeration [kWh/PE/year] Rate of electricity consumption for aeration [%]
- Level of self-sufficiency [%]
- Specific biogas production [L/PE/day]

A detailed set of data can be found in the Haberkern [169]. They focused on biological treatment plants that are sized above 5000 PE because these treatment plants consume most of the electricity in Germany. Target values can be achieved primarily by biological treatment plants that have anaerobic production of biogas (Table 1).

Table 1. Target and existing values of process indicators of specific electricity consumption [168].

Treatment Stage	Process indicator	Unit	Target value	Existing value	
	WWTPs siye		> 5000 PE	5000 - 10000 PE	> 10000 PE
Overall process	Electricity consumption	kWh/PE/year	18	35	30
Overall anaerobic stage	Energy sustainability	%	100	-	30
Anaerobic stage	Heat energy	kWh/PE/year	0	-	3
Anaerobic stage	Biogas production	L/PE/day	30	-	20

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Aeration aerobic stage	Electricity consumption	kWh/PE/year	10	18	16
Pumps	Electricity consumption	Wh/m³/m	4	-	6

In the Baumann and Roth study [170], they focused mainly on the nitrification process at smaller sewage treatment plants and evaluated the existing (Table 2) and target values (Table 3). In this case, PE is based on BPK5 (60 g/person/day) was used to calculate the specific electricity consumption [170].

Table 2. Typical values of the processes of specific energy consumption in kWh/PE//year [170].

Specific electricity consumption [kWh/PE/year]					
WWTPs size	< 1000 PE	1000 – 5000 PE	5001 - 10000 PE	10001 - 100000 PE	> 10000 PE
Aeration basin	50	40	35	-	-
Biodisc	34	23	18	-	-
Trickling filter	32	25	20	25	25
Extended aeration	70	45	38	34	-
Activated sludge	60	40	34	30	27

Table 3. Target values of the processes of specific energy consumption in kWh/PE/year [170].

Specific electricity consumption [kWh/PE/year]					
WWTPs size	< 1000 PE	1000 – 5000 PE	5001 - 10000 PE	10001 - 100000 PE	> 10000 PE
Aeration basin	32	30	25	-	-
Biodisc	23	18	15	-	-
Trickling filter	20	17	15	18	18
Extended aeration	38	28	23	20	-
Activated sludge	32	24	20	18	18
Activated sludge and trickling filter	-	-	-	18	18

Haberkern [169] stated, that the largest consumers of electricity in the process of wastewater treatment are aerators, which consume between 50% and 60% of all electricity, a lot of energy is also used for mixing (in the denitrification reactors, reactors with activated sludge, Etc.) and for pumping of wastewater in different stages. To maintain effective aeration of WWTPs over 10,000 PE, adequate aeration consumes 16 kWh/PE/year, and a target value should be set to 10 kWh/PE/year. In the study of reducing the consumption of specific electricity for aeration in the aerobic stage on a monthly level, they achieved a reduction from 18.9 kWh/PE/year to 13.3 kWh/PE/year, which means 450 MWh/month of saved electricity.

It is estimated that domestic wastewater has 10-times more energy than it is required for its treatment [171]. Energy is hidden in the wastewaters as chemical, thermal, and hydraulic energy. Considering the average chemical oxygen demand (COD) of 500 mgL^{-1} in the wastewater, the chemical energy of the wastewater is estimated to be 1.8 kWh m^{-3}. Despite the high energy content, due to the thermodynamic and technological limitations, only part of this energy is recovered, and many challenges still must be overcome to recover all this energy in an economically viable way [172].

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8. Future Perspectives

The ongoing legislative process of the amended municipal wastewater treatment directive [1] represents a viable platform for further development and practical applications of sustainable processes and technologies for municipal wastewater treatment. Wastewater treatment enables sustainable management of natural resources by improving clean water supplies and minimizing pressure on natural resources. It creates pathways for clean energy production and use, and significantly supports social and economic activities [3,4].

Although the primary function of a municipal wastewater treatment plants is to reduce wastewater pollution, the process generates several potentially valuable "by-products" including treated water, biogas and sludge. Treated WW can be reused in various applications. Biogas can be used for electricity generation, heating, transportation or even as a chemical raw material. Sludge can either be recycled into the soil as a conditioner or used through thermochemical/biochemical processing to obtain e.g., hydrocarbons, energy (e.g., heat and syngas), or valuable raw materials (e.g., phosphorus). Thus, MWWTPs offer great potential for a circular economy by implementing the 3R principles (reduction, reuse, and recycling) [44].

Regeneration of nutrients from municipal wastewater by microalgae could potentially reduce energy consumption for nitrogen and phosphorus by 47% and 240%, respectively. Produced treated wastewater can be used for irrigation, while biomass from microalgae represents a potential sustainable alternative source of nitrogen and phosphorus with a significant reduction in the consumption of inorganic fertilizers [45].

Nitrous oxide (N_2O) and methane (CH_4) are two primary greenhouse gases (in addition to biogenic CO_2) that are produced during the collection, treatment, and discharge of wastewater. Among these, N_2O has a significantly higher 100-year global warming potential, being 273 times more effective than carbon dioxide (CO_2) on a mass equivalent basis, while CH_4 is 28 times more effective [12]. However, the amounts of N_2O and CH_4 generated in a wastewater treatment plant (WTP) can vary widely depending on the specific treatment processes used and the size of the facility [13]. Decreasing of total energy consumption and all greenhouse gas emissions in the whole EU is possible by improving the treatment processes, better use of sewage sludge, increasing energy efficiency, and by higher rate of use of renewable resource technologies [1].

A lot of innovative and novel wastewater treatment processes, reactors and technologies have been developed and applied in the field. These include ammonia-oxidizing archaea (AOA), anaerobic ammonium oxidation bacteria ANAMMOX, complete ammonia oxidation bacteria (COMAMMOX), iron-reducing bacteria that cause anaerobic ammonium oxidation (FEAMMOX) and denitrifying anaerobic methane oxidation bacteria (DAMO) for biological nitrogen removal (BNR) using new microorganisms that use new metabolic mechanisms [52]. Compared to conventionally used nitrifying or denitrifying bacteria, these new microorganisms have better physico-chemical tolerance and are also more efficient in terms of greenhouse gas emissions. They represent potential microbial communities for new high-performance and energy-saving technologies for nitrogen removal from wastewater.

During shortened nitrification (nitrification), significant investment and operating savings can be achieved by using the Anammox process. Ammonium ion-oxidizing nitrifying bacteria (AOB) oxidize 57% of input ammonium ions to nitrite, which saves approx. 50-60% of energy (oxygen consumption) without the need for an organic substrate [72]. Anammox microorganisms transform the remaining ammonia nitrogen and nitrogen gas. The production of excess sludge is approximately 80% less in this process. In the anammox process, is transformed up to 13% of the input nitrogen into nitrates, which are partly heterotrophically denitrified in the process [53].

Simultaneous nitrification-denitrification (SND) using oxic and anoxic conditions and appropriate microbial populations is suitable for the biological removal of nitrogen from municipal wastewater [56]. Combining anammox with denitrification has the potential to increase nitrogen removal rates and reduce energy consumption. SND studies show the overall nitrogen removal efficiency in SND systems is ≥90%. Anammox denitrification reaches 77% efficiency. The advantages of SND are its simplicity of operation and management, low energy costs, economy, and efficiency.

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Heterotrophic nitrification and aerobic denitrification (HNAD) eliminate the shortcomings of current biological nitrogen removal systems [82]. The existence of some heterotrophic nitrifiers capable of nitrifying using organic carbon was discovered [83–85]. Many of them can denitrify the products of their nitrification, i.e., nitrates and/or nitrites, to N_2 [86]. Thus, they can simultaneously use dissolved oxygen and nitrates and thus allow nitrification and denitrification to take place in one reactor under oxic conditions. In other words, they use nitrates/nitrites as the final electron acceptor. SND implemented is cost-effective (22–40% reduction in carbon consumption and approximately 30% reduction in sludge production) [74].

SND technology overcame the limitations of commonly used nitrogen removal technologies and provides a progressive technology for this biological process [91–93]. However, this technology makes it possible to integrate N and P removal processes and phosphorus recovery as well. The simultaneous nitrification, denitrification, and phosphorus removal (SNDPR) is mediated by the integration of denitrifying phosphorus-accumulating DPAO organisms into the SND process. Simultaneous removal of nitrogen and phosphorus under aerobic or anoxic conditions occurs in a single reactor without alternating anaerobic/anoxic/oxic conditions [94].

Compared to conventional BNR technologies, new technologies differ mainly in improving efficiency, and saving operating costs and energy [64,65].

An important tool for optimizing WWTP operation and reducing energy consumption for aeration (25 to 40%) while maintaining the required quality of discharged wastewater is the use of mathematical models and control systems in real-time. Energy savings can also be achieved by implementing reliable ammonium sensors in aeration control loops and cheaper sensors developed using multiple linear regression, neural networks, and redox potential and pH sensors [8].

MWWTPs belong to the main anthropogenic sources for the release of micropollutants and emerging contaminants (ECs) into the environment. Secondary treatment processes (e.g., conventional process using activated sludge) and tertiary processes (e.g., disinfection and filtration) are not very effective in removing ECs from WW. Prospective methods of heterogeneous photo-Fenton reaction, photocatalytic ozonation, photocatalytic membrane processes, electrochemical oxidation, and hybrid processes for ECs removal were investigated, but due to technological limitations and costs, they were not applied. However, they can be included in the long-term perspective of the EC removal method. ECs can be effectively removed from municipal WW using consolidated advanced methods of PAC/GAC adsorption, ozonation, nanofiltration, or reverse osmosis membranes. Several facilities using AC adsorption and ozonation have recently been implemented at full scale in a cost-effective manner in Germany and Switzerland. The most expensive processes include nanofiltration / reverse osmosis [130].

Despite sludge presenting only a few percent of the volume of the processed wastewater volume, its treatment costs represent up to 50 % of the WWTP operating costs [131]. To contribute to more sustainable sludge management, the economic, social, and environmental aspects of all the sludge treatment processes need to be considered. In the review conducted by Carrere et al. [136] a comparison of different pre-treatment methods was made. It was reported that pre-treatment increased biogas production from 15 to 90%. A comparison of the efficiency of methods showed the thermal methods were the most effective in terms of increased biogas production, while the energy input was higher than at the other methods.

The main goals of modernization and construction of new wastewater treatment plants should be based on:

- Implementation of different treatment processes in the existing systems. Treatment methods like trickling filters, lagoons, constructed wetlands, and adsorption-biology systems are comparatively more energy-efficient. However, energy consumption increases with implementation of advanced treatment processes used for nutrient removal and sludge conditioning. The energy demand for advanced biological treatment with nutrient removal and filtration is approximately 50% higher than that of conventional WWTPs [173].
- Adapting the WWTP process to a new energy input from a renewable mix, including, small-scale (less than 10 MW) photovoltaic (PV) and wind energy sources;

- Increased use of the renewable sources (PV and wind) in the WWTP;
- Different models and scenario-based optimization approaches enable engineers to optimize the design of infrastructure and evaluate operational costs, facilitating long-term efficiency planning; and
- Developing an intelligent system capable of managing the input of energy from different sources. It should also be able to regulate the overall energy input according to the precise demand of the WWTP at every stage of the process.

LIFE13-ENV-ES-000704 (2017) project [164] showed that energy consumption in Europe for WWTP can be reduced by 28.47% in the aeration stage with the integration of renewable energy sources. These actions also lead to a reduction in the carbon footprint of around 46.80 tons of CO_2 per year for every 100 kW from renewable sources. The project also emphasizes further benefits of such approach, not just directly for WWTPs systems, but also for the agricultural and industrial sectors, as well as the public sector, that use treated wastewater for a range of purposes.

There is still a need for more information regarding nutrient removal, polishing treatments, and operational costs of nature-based wastewater treatment technologies, as noted in studies [174]. There are numerous technologies for nutrient removal available, but these processes still result in high operational and investment costs that cut down cost-effectives. However, the energy efficiency of wastewater treatment systems should be optimized by the effective utilization of solid treatment products by biogas or compost production, while wastewater treatment could be optimized by the production of other value-added products (algae, etc.).

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Abbreviations

ABR	Anaerobic baffled reactor
AC	activated carbon
AD	anaerobic digestion
ANAMMOX	ammonium oxidation bacteria
AOA	ammonia-oxidizing archaea
AOB	ammonia-oxidizing bacteria
AOP(s)	Advanced oxidation process(es)
BABE	bioaugmentation batch treatment
BOD_5	Biochemical oxygen demand
CE	circular economy
COD	Chemical oxygen demand
COMAMMOX	complete ammonia oxidation bacteria
CW(s)	Constructed wetland(s)
EC	emerging contaminants
EmA	emergency analysis
EU	European Union
FCO(s)	four prospective circular options

FEAMMOX	iron-reducing bacteria
FNA	free nitric acid
FWS	free water bodies
GHG	greenhouse gas
GTS	grease trap sludge
GWP	global warming potential
HRT	hydraulic retention time
HSSF	horizontal subsurface flow
LCA	life cycle analysis
LCCA	life cycle costing assessment
MABR	membrane anaerated biofilm reactor
MFA	material flow analysis
MP(s)	micropollutant(s)
MWWTP(s)	municipal wastewater treatment plant(s)
NOB	nitrite oxidizing bacteria
PAO(s)	polyphosphate-accumulating organisms
PE	population equivalent
PN	partial nitritation
PV	photovoltaic
SND	simultaneous nitrification-denitrification
SRT	solid retention time
TKN	Total Kjeldahl Nitrogen
TN	Total nitrogen
TP	Total phosphorous
TSS	Total suspended solids
TWS	tidal flow systems
UASB	up-flow anaerobic sludge blanket reactor
VSSF	vertical subsurface flow
WW	wastewater
WWTP(s)	wastewater treatment plant(s)

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