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Review

# Circular Economy in Wastewater Treatment Plant—Water, Energy and Raw Materials Recovery

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**Abstract:** Nowadays, the main challenge for industrial and municipal enterprises is related to the tightening regulations and recommendations regarding environmental protection, which have been included in the circular economy (CE) package. Enterprises from all sectors, including water and sewage management, are obliged to actively participate in the CE transition. Modern wastewater treatment plants (WWTPs) should include actions aimed at a more sustainable use of available resources (water, energy, raw materials) to contribute to the protection of natural resources. In this way, they can be treated as resource facilities. This paper proposes a conceptual framework for a 'Wastewater Treatment Plant of the Future' that includes several technological solutions that take into account circular management of waste streams generated in WWTPs, such as wastewater (WW), sewage sludge (SS) and sewage sludge ash (SSA). Many actions have been already taken to modernize and build WWTPs that can respond to current and future challenges related to environmental protection. In the case of a CE 'Wastewater Treatment Plant of the Future', the recovery of water, energy and raw materials from available waste streams is strongly recommended. The implementation of CE solutions in analyzed facilities is incorporated into many strategies and policy frameworks, such as national and international (including European) documents. The proposed CE solutions could indirectly contribute to satisfying significant technological, social and environmental needs of the current and future generations, which is in line with sustainability principles.

**Keywords:** wastewater; wastewater treatment plant; WWTP; circular economy; CE; water; energy; raw materials; phosphorus



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## 1. Introduction

In recent years, regulations on the functioning of industrial and municipal facilities, including wastewater treatment plants (WWTPs), have been increasingly tightened [1]. This is dictated by the increasing importance of issues related to environmental protection, as well as various recommendations and requirements in the field of counteracting climate change [2], which is one of the most important threats to modern civilizations (next to epidemic and terrorist threats). The water and wastewater management sector faces various challenges related to the implementation of pro-environmental requirements, but also, on the other hand, there are some opportunities for further development of this sector in the context of water, energy and raw materials management [3,4]. Those opportunities are mainly related to the implementation of solutions in the field of circular economy (CE) [5], which is aimed at the protection of natural resources from primary deposits and more sustainable management of secondary raw materials, i.e., those derived from waste materials [6,7]. In both of the presented pathways (raw materials management and waste management), WWTPs are very promising plants in which these activities can be carried out. In the first place, water, energy and raw materials can be managed in a more rational way through the use of water-, energy- and material-saving installations and solutions in the plant. On the other hand, those resources could be recovered in WWTPs through the use of various methods of recovery and recycling, e.g., water recovery for agricultural purposes [4], energy for biogas production [8], or phosphorus (P) compounds from sewage and sewage sludge [9,10]. The selected WWTPs that already use these solutions, which are based on the latest technologies available for water and wastewater management, set directions for newly built and modernized wastewater treatment plants around the world [11,12], implementing the ideas of sustainable development (SD) and circular economy.

On the European level, it is clearly indicated that the treatment of municipal wastewater is fundamental to ensure public health and environmental protection [13]. In the last few decades, systems of municipal wastewater treatment have improved in all parts of EU countries [14]. The most important regulation on municipal wastewater is the Council Directive 91/271/EEC concerning urban waste water treatment (UWWTD), which was adopted in 1991, to protect a water environment from inappropriate human activity in the form of discharges of insufficiently purified municipal and industrial wastewater that thus threaten human health and life [4,15]. It is worth noticing that in 2022, the EC proposed a revised version of the directive that is extended by a comprehensive impact assessment, adapting it to the newest standards. The revised directive includes several aspects of the CE. The following elements are considered to be included or extended: further reduction in pollution, energy consumption and greenhouse gas (GHG) emissions; improvement of water quality by extending requirements on urban wastewater pollutions; improvement of access to sanitation; increase in industry responsibilities for generated micropollutants (environmental fees); implementation of obligatory monitoring of pathogens in wastewater; be an active actor (e.g., sector) in the CE transition [16].

Most municipal WWTPs focused for many years on wastewater and water purification and discharge to the environment. However, in the last few decades, a special focus has been placed on new solutions that can provide water, energy and raw materials (e.g., nutrients or organic materials) for various processes such as reuse, recycling and recovery [3]. In this context, WWTPs can be treated as resource hubs that are a part of the CE transition [17]. Therefore, there is a justified need to develop a new scope of activities of WWTPs, which will take into account the possibility of sustainable management of resources, in accordance with the CE idea. This paper proposes a conceptual framework for a 'Wastewater Treatment Plant of the Future' that includes several technological and organizational solutions that take into account circular management of water, energy and raw materials in the WWTP. The implementation of CE solutions in these facilities is recommended both in scientific papers and in law restrictions and strategies. The structure of the current review is as follows: presentation of the importance of wastewater treatment plants in the CE model; methods used in the current paper; overview of the importance of water, energy and raw materials in the CE model; characteristics of the WWTPs in the EU; concept of CE WWTP 'Wastewater Treatment Plant of the Future'; discussion; and conclusions.

Only a few earlier papers present the concept of CE in a treatment plant, but none indicate a comprehensive approach and areas of a 'Wastewater Treatment Plant of the Future' based on CE principles. The results of this paper may be of key importance for the further development of the circular economy concept in WWTPs—they can help scientists in developing further CE solutions as well as treatment plant operators who are looking for new solutions in the field of CE in WWTPs in the area of water, raw materials and energy management.

## 2. Materials and Methods

The methods used to achieve the assumed objectives of the study included the development of a conceptual framework for a 'Wastewater Treatment Plant of the Future' that contains a visual representation of theoretical constructs (specific elements of CE WWTP) of interest. The development of a conceptual framework began with conducting a detailed review of the literature, to set a scope and boundaries of the conceptual intended model. The research is presented in Figure 1. Therefore, in the first stage of this research, identification and verification of the importance of CE transformation potential in WWTPs were conducted. This included a comprehensive review and assessment of strategic documents dedicated to the CE implementation on the European level. This stage of research was conducted via the use of the desk research method, which involved the collection of data from existing resources available in public scientific databases, libraries and websites. The main primary literature was searched in full-text scientific databases, such as Elsevier Scopus, Elsevier Science Direct, Google Scholar, Wiley Online, Web of Knowledge, Baz-Tech, and Multidisciplinary Digital Publishing Institute (MDPI), as well as official, multilingual, free database collecting legal acts of the European Union (EUR-lex) and statistics (Eurostat). The other data sources included specific CE-related reports, published by various pro-environmental organizations, such as the International Water Association (IWA) and Ellen McArthur Foundation. The following keywords were used to collect appropriate documents: 'water', 'wastewater', "wastewater treatment', 'wastewater treatment plant', 'WWTP', 'sewage', 'sewage sludge', 'sustainable development', 'circular economy', 'CE', 'reuse', 'removal', 'recycling', 'energy', 'nutrients', 'phosphorus', 'nitrogen', 'reclamation' and 'recovery'. In the second stage of this research, obtained literature was organized around the topic, with a focus on the three main assumed aspects—water, energy and raw materials in WWTPs. Then, a conceptual framework for a 'Wastewater Treatment Plant of the Future' was proposed, based on theory. This was presented in the form of a diagram, with individual elements (CE blocks in WWTP) with linkages—arrows that represent the hypothesized relationships between elements. The following model is not meant to exhaust the possibilities of connecting independent and dependent elements. There could be a flexible approach in the various WWTPs that for example skips some blocks or adds new ones.

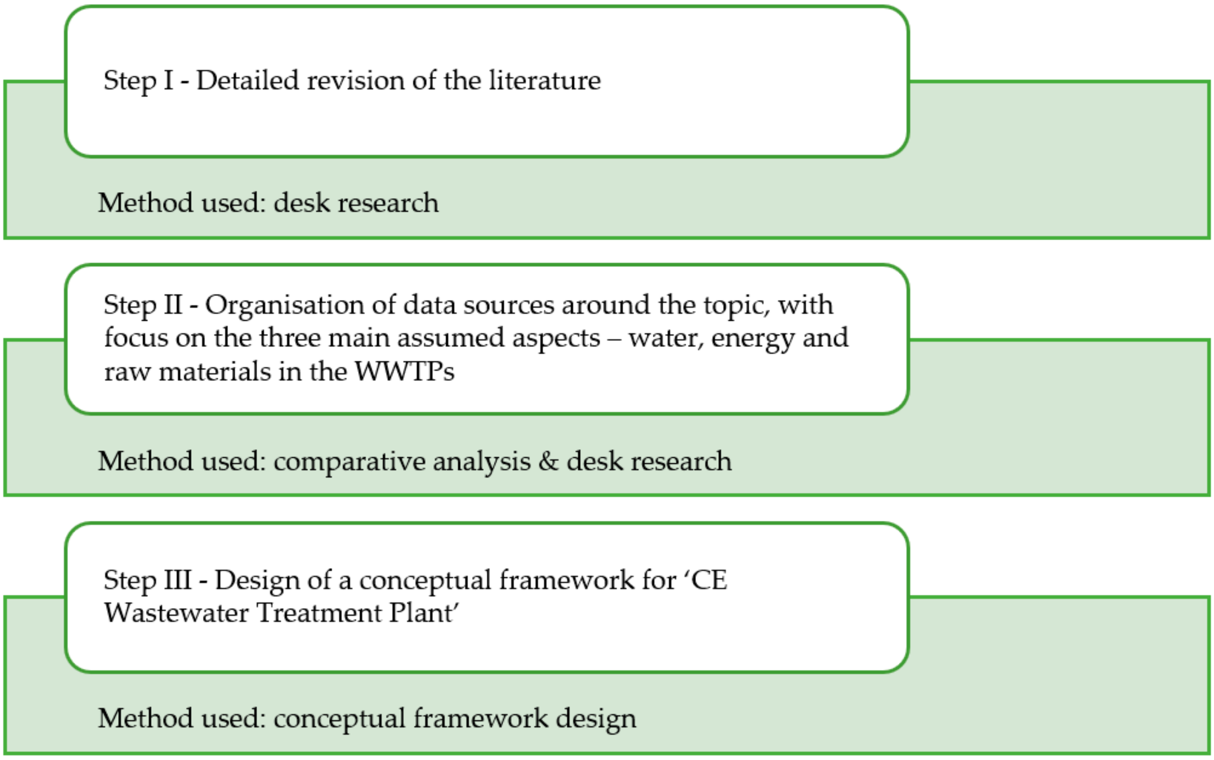


**Figure 1.** The research design for developing a conceptual framework of the Wastewater Treatment Plant of the Future.

The results of the study, supported by discussion and comparison of results of various authors, are presented in the sections below.

## 3. Results

This section describes the results of the study, and it is divided into three subsections, dedicated to strategic objectives.

*3.1. Importance of Water, Energy and Raw Materials in CE*

Circular management of water, energy and raw materials is an integral part of the CE initiative in the water and wastewater sector. The EC's strategic documents emphasize the importance of these elements, which is why the most important recommendations in this field are listed below. An inventory of water, energy and nutrient aspects in WWTPs in the European policy on CE is presented in Table 1.

**Table 1.** Inventory of water, energy and nutrient aspects in WWTPs in the EU policy on CE.

| Policy Area | Law Document | Recommendations and Objectives |
| --- | --- | --- |
| Circular Economy | Zero-waste program for Europe (COM no. 398, 2014) [18] | 1. Improve rational management of primary resources and sustainable management of secondary resources (waste) as strategic areas of the CE implementation in the EU.<br>2. Expand the scope of indicators in the Resource Efficiency Scoreboard, including also water, land and other non-carbon materials.<br>3. Develop a policy framework dedicated to phosphorus management, to strengthen its recycling, support innovation, improve market conditions and mainstream its circular and sustainable use in the EU law on food, water, fertilizers and waste.<br>4. Reduce usage of materials and energy in production and use phases (improve efficiency).<br>5. Improve energy recovery, such as waste-to-energy recovery and usage of biofuels. |
| | First CE Action Plan (COM no. 614, 2015) [6] | 1. Set legislative proposals on waste management.<br>2. Improve market for secondary raw materials such as nutrient-rich waste generated in WWTPs.<br>3. Improve market for water reuse, especially in the context of water reuse from municipal wastewater to agriculture. |
| | Second CE Action Plan (COM no. 98, 2020) [7] | 1. Development of the Integrated Nutrient Management Action Plan (INMAP), to promote more sustainable usage of nutrients and their recovery from waste.<br>2. Promotion of water reuse for agriculture and considering other purposes, such as industrial processes.<br>3. Promotion of circularity in planned revisions of the National Energy and Climate Plans and climate policies. |
| Fertilizers | Regulation on EU fertilizing products (EU 2019/2019) [19] | 1. Set common rules on quality, safety and labeling requirements for selected fertilizing products.<br>2. Set limits for toxic pollution.<br>3. New CE fertilizing products, including organic fertilizers, organo-mineral fertilizers, inhibitors, soil improvers, growing media or plant biostimulants. |
| Water | Regulation on EU water reuse (EU 2020/741) [20] | 1. Set minimum requirements for water quality.<br>2. Establish monitoring and provisions on risk management to ensure safe usage of reclaimed water as a part of integrated water management.<br>3. Contribution to the objectives of Directive 2000/60/EC through addressing water scarcity and resulting pressure on water resources. |

In the first official EU document on CE 'zero-waste program for Europe' [18], a lot of attention has been paid to improving rational management of primary resources and sustainable management of secondary resources (waste) as strategic areas of the CE implementation in the EU. An important recommendation was to indicate the necessity of monitoring not only the use of resources and other carbon-related materials, but also other aspects such as water or land management in the Member States. Therefore an expansion of the scope of indicators in the Resource Efficiency Scoreboard was proposed. Moreover, phosphorus raw materials have been indicated as a critical area for further policy development, because phosphorus is a critical raw material (CRM) for the EU [21], and its current usage creates P losses at every stage. The P framework policy should improve not only its recycling, but also market conditions for secondary sources. Moreover, it was assumed that innovative P recovery technologies could foster innovations and accelerate sustainable use of not only P fertilizers, but also food, water and P-rich waste. With the improvement of sustainable management of materials and nutrient-rich waste, increasing energy efficiency was also mentioned as a key area of CE implementation. The improvement of energy recovery in the water and wastewater sector has prospects in WWTPs in context of waste-to-energy recovery and usage of softer biofuels, which should include non-reusable and non-recyclable waste. The integrated use of biological resources and waste for production of energy, food and bio-based products was also mentioned as a part of Bioeconomy Strategy [22], which also includes the water and wastewater sector. It was also clearly stated that Horizon 2020 (the Framework Programme for Research and Innovation that was implemented from 2014 to 2020, with a budget of nearly EUR 80 billion) should support initiatives to improve the sustainable management of various primary and secondary resources, such as waste, water, energy and raw materials [18].

The first CE action plan of the EU was proposed in 2015 [6]. It included several legislative proposals on different areas of economic activity in European countries, mainly dedicated to long-term objectives for sustainable waste management. One of the key legislative proposals was proposed for fertilizers and water reuse. The EC assumed initiatives on ‘From waste to resources: boosting the market for secondary raw materials and water reuse’. The proposal for revision of fertilizer regulations in the EU was proposed, as was the revision of water-related legislation. Both are clearly connected with the operation of WWTPs. In the context of fertilizer usage coming from secondary sources, nutrient-rich wastes, such as wastewater, sewage sludge and sewage sludge ash, were mentioned. It should be underlined that in 2016, as the first official implementation of the CE initiative in the EU, a proposal for CE-marked fertilizers was proposed [23]. It was proposed to supplement EU regulations on fertilizer usage to include the possibility to produce and sell CE-marked organic fertilizing material (e.g., compost and digestate). In 2019, the final version of the new regulation on fertilizer was published. It presents harmonization rules for organic fertilizers, organo-mineral fertilizers, inhibitors, soil improvers, growing media or plant biostimulants. The waste generated in the water and wastewater sector was indicated as a source of nutrients for the indicated CE products [19].

On the other side, the WWTP should play a strategic role in the planned changes to the EU laws regarding the reuse of water from municipal sewage, which is intended for agricultural use. Therefore, the EC in the first CE action plan proposed the establishment of a legal framework for water reuse for irrigation and groundwater recharge, as well as the promotion of cost-effective and safe water reuse, by developing guidelines for integrating water reuse into water planning and management, innovation support (through the European Innovation Partnership and Horizon 2020), investments in WWTPs, and the inclusion of best practices in relevant Best Available Techniques reference documents (BREFs) [6]. Following these declarations, in 2020, the EC presented a new regulation on water reuse with a set of minimum requirements for the reuse of municipal wastewater for agricultural purposes [20]. Those requirements cover water quality, water monitoring and risk management (including the development of risk management plans) for the safe use of reclaimed water in agriculture. This regulation has to be adopted by all EU countries by the middle of 2023 as an element of CE promotion and implementation. The scope of these recommendations is part of integrated water management in the Member States. Water reuse may also be positively correlated with the management of biogenic raw materials if municipal wastewater treatment technologies are used, which will allow controlling the content of N or P in reclaimed water directed to agriculture. It can also support the recovery of nutrients in WWTPs. The WWTPs could play a role of a reclamation facility that is defined as an 'urban WWTP or other facility that further treats urban waste water that complies with the requirements set out in Directive 91/271/EEC in order to produce reclaimed water', and a reclamation facility operator is defined as ‘natural or legal person, representing a private entity or a public authority, that operates or controls a reclamation facility’. In general, a water reuse system needs to be developed to cover infrastructure and all other technical elements that are necessary for producing, supplying and using reclaimed water. A dynamic development of implementation projects in this field can be expected in the coming years.

Currently in the force is a second CE action plan, dedicated to a cleaner and more competitive Europe [7]. The most important element of this plan in the context of the future operation of WWTPs is the proposition to develop the Integrated Nutrient Management Action Plan (INMAP), which should include a review of directives on wastewater treatment and sewage sludge as well as an evaluation of natural means of biogenic raw material removal, e.g., by algae. The proposition of the INMP was presented by the European Sustainable Phosphorus Platform (ESPP), which actively supports the EC in the creation and consultation of documents in the fields of water and sewage management, fertilizers and distribution [24]. Water and nutrients are connected in the second CE action plan with the food sector. In this context, the food sector is directly connected with new water reuse regulation, which is supposed to encourage circular approaches to water reuse in agriculture. There is a declaration by the EC to facilitate water reuse and its efficiency, not only in agriculture but also in industrial processes. From the perspective of nutrients, a reduction in extensive resource extraction (by nutrient recovery from waste) could contribute to restoring biodiversity and natural capital in the EU. Currently, half of total GHG emissions and more than 90% of biodiversity loss and water stress are consequences of resource extraction and processing; therefore, the CE model as a strategic block of the European Green Deal (EGD) promotes a climate-neutral, resource-efficient and competitive economy. Because circularity is a prerequisite for climate neutrality, which is the main objective of the EGD, special attention is also paid to energy efficiency. There is a strong recommendation to promote circularity in planned revisions of the National Energy and Climate Plans and climate policies [7].

It is worth noting here that the recommendations in the field of water, energy and raw materials management in the presented areas not only apply to the water and wastewater management sector, but also force the creation of so-called industrial symbiosis (IS) [25], which is also indicated as one of the foundations of building CE [18]. Industrial symbiosis is based on the principle of voluntary cooperation of two or more entities and obtaining mutual benefits [26]; i.e., waste from one sector can be a valuable source of raw materials in another sector [27], e.g., sewage sludge can be a source of biogenic raw materials in the fertilizer sector [28], while reclaimed water from municipal wastewater can replace water from water intakes in agriculture [4].

### *3.2. Wastewater Treatment Plants*

Wastewater management is a part of water management and municipal management. It covers, in particular, the following issues: water supply systems for collective water supply, wastewater systems for sewage disposal and treatment, individual water supply systems and wastewater systems, sewage sludge disposal, rainwater drainage and appropriate treatment, and drainage of areas. Wastewater management is a special type of pressure affecting water, as the discharge of wastewater into waters or into the ground has a significant impact on the deterioration of water quality. In general, four main activities are implemented as part of water and wastewater management [29]:

- Modernization of water supply systems and devices guaranteeing the water quality required by law, intended for supplying the population;
- Construction, extension and modernization of sewage systems and WWTPs in areas with concentrated buildings and urbanized areas;
- Improving the efficiency of removing harmful substances from wastewater discharged into surface waters;
- Preventing eutrophication of waters under the influence of pollution, including from diffuse sources.

In the UWWTD, special attention is paid to WWTPs, which are defined as facilities in which a combination of different processes of pollutant removal (physical, chemical, biological) are used to remove pollutants [30]. In a broader sense, a WWTP is a set of equipment and technological facilities as well as accompanying facilities (which are necessary for proper functioning, service and control) intended for wastewater treatment. According to the type of inflowing sewage, the following are distinguished:

- Municipal wastewater treatment plants;
- Industrial wastewater treatment plants;
- Special-purpose wastewater treatment plants.

In turn, according to the type of wastewater treatment methods used and the processes directly related to them, we can distinguish mechanical treatment plants, chemical treatment plants and biological treatment plants.

One of the most important elements of the WWTP is the sewer, which needs to be built to collect wastewater and transport it to WWTP [31]. In the WWTP, various levels of treatment are applied. They usually include the following (Figure 2):

- Pre-treatment, which includes physical removal of large objects (e.g., rags and plastics) and smaller objects (e.g., grit from the wastewater);
- Primary treatment, which includes removal of fine particles; wastewater is kept in a dedicated tank where heavier solids fall to the bottom, and lighter solids or fat float to the surface; settled and floating solids are separated; remaining liquid is directed to secondary treatment or discharged to the natural reservoir;
- Secondary treatment (biological treatment),which removes all remaining organic matter, suspended solids, selected viruses, bacteria and parasites; it could also remove nutrients or chemical substances to some extent;
- Advanced treatment (more stringent treatment), which is applied for the removal of the remaining nutrients before discharge into sensitive waters (e.g., through disinfection that can be used for further removal of viruses, bacteria and parasites, or other remaining chemicals and harmful substances).

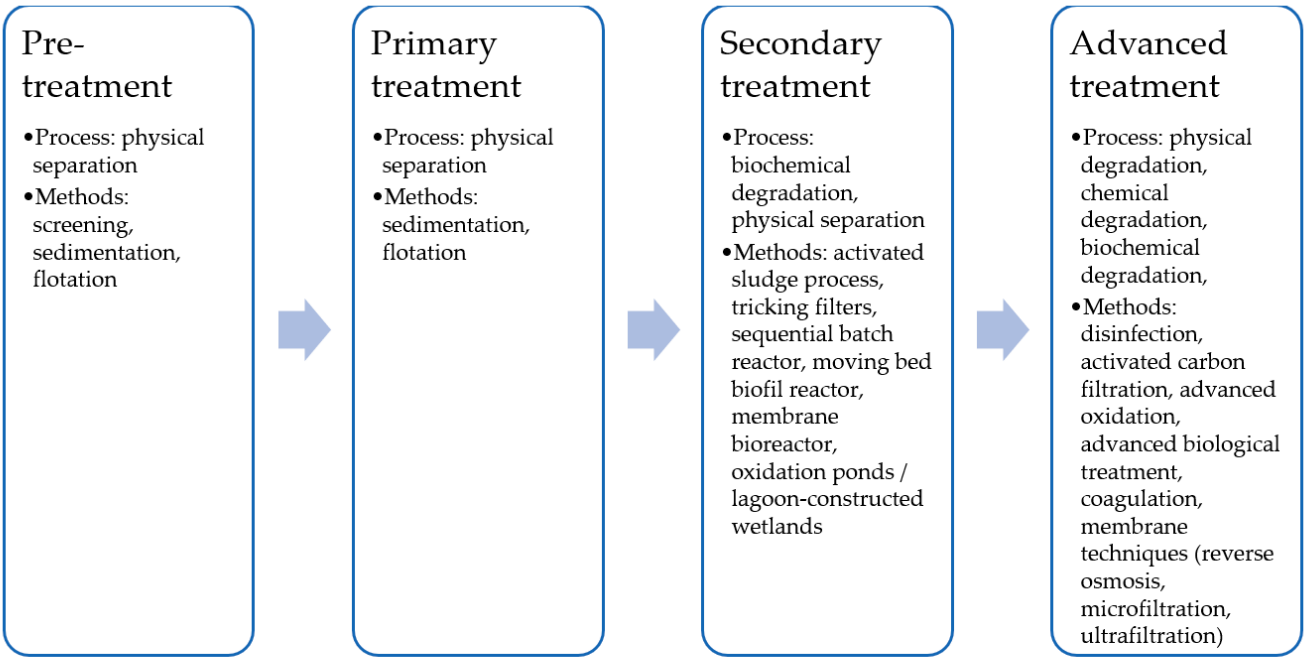


**Figure 2.** Wastewater treatment processes in WWTPs.

In the last year, a lot has been done to improve sewage systems across European countries. Currently, most of the EU countries collect and treat wastewater at the tertiary level, coming from most of the population. However, there are still some countries where less than 80% of the residents are connected to public municipal wastewater treatment systems [17]. The countries with the highest proportions of citizens connected to WWTPs are Luxembourg (100%), the Netherlands (99.5%), Malta (98.9%), Austria (96%) and Denmark (92%), while the lowest proportions are observed in Croatia (54.6%) and Romania (56%).

Data presenting populations connected to urban wastewater collection and treatment systems in the EU countries are presented in Table 2.

**Table 2.** Population connected to urban wastewater collecting and treatment systems in the EU countries (in percentage, %).

| No. | Country | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **Austria** | n.d. | 93.90 | n.d. | 94.50 | n.d. | 95.00 | n.d. | 95.20 | n.d. | 95.95 | 95.95 | 96.04 |
| 2 | **Belgium** | 88.50 | 82.20 | 84.40 | 86.71 | 87.21 | 87.48 | 87.79 | 87.96 | 88.08 | 87.22 | 86.88 | 87.52 |
| 3 | **Bulgaria** | 70.40 | 70.62 | 74.09 | 74.33 | 74.70 | 74.88 | 75.50 | 75.69 | 76.03 | 76.19 | 76.42 | 76.25 |
| 4 | **Czechia** | 81.10 | 82.30 | 83.40 | 83.00 | 84.70 | 83.90 | 84.20 | 84.70 | 85.50 | 85.50 | 85.50 | 86.10 |
| 5 | **Denmark** | 89.80 | 90.00 | 90.30 | 90.50 | 90.60 | 90.70 | 90.90 | 91.40 | 91.60 | 91.70 | 91.80 | 92.00 |
| 6 | **Germany** | n.d. | 95.70 | 95.90 | 96.01 | 96.16 | 96.48 | 96.80 | 97.12 | n.d. | n.d. | n.d. | n.d. |
| 7 | **Estonia** | 81.00 | 82.00 | 82.00 | 82.00 | 82.00 | 82.00 | 83.00 | 83.00 | 83.00 | 83.00 | 83.00 | 83.00 |
| 8 | **Finland** | 83.00 | 83.00 | 83.00 | 83.00 | 83.00 | 85.00 | 84.00 | 84.00 | 85.00 | 85.00 | 85.00 | 85.00 |
| 9 | **Ireland** | 77.00 | n.d. | 63.80 | 63.89 | 63.97 | 64.06 | 64.14 | 64.22 | 64.22 | 64.22 | 64.22 | n.d. |
| 10 | **Greece** | 87.30 | 87.30 | 88.10 | 92.04 | 92.80 | 92.80 | 93.40 | 93.40 | 94.80 | 94.80 | 94.20 | n.d. |
| 11 | **Spain** | n.d. | 98.00 | n.d. | 95.58 | n.d. | 96.39 | n.d. | 96.52 | n.d. | 96.52 | n.d. | n.d. |
| 12 | **France** | n.d. | 82.00 | 82.00 | 82.00 | 82.00 | 82.00 | 82.00 | 82.00 | 82.00 | 82.00 | 82.00 | 82.00 |
| 13 | **Croatia** | n.d. | n.d. | 54.60 | 54.60 | 54.60 | 54.60 | 54.60 | 54.60 | 54.60 | 54.60 | 54.60 | 54.60 |
| 14 | **Italy** | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | 87.80 | n.d. | n.d. |
| 15 | **Cyprus** | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | 82.65 | n.d. | n.d. |
| 16 | **Latvia** | 65.71 | 65.22 | 71.41 | 72.58 | 73.34 | 73.12 | 74.81 | 72.99 | 77.75 | 75.78 | 80.91 | 80.11 |
| 17 | **Lithuania** | n.d. | 63.77 | 65.12 | 67.00 | 67.00 | 69.61 | 72.45 | 73.67 | 73.91 | 75.88 | 76.64 | 77.08 |
| 18 | **Luxembourg** | n.d. | 97.10 | 99.00 | 99.00 | 99.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| 19 | **Hungary** | 72.00 | 72.30 | 72.70 | 74.00 | 74.99 | 76.64 | 78.56 | 80.65 | 81.37 | 82.00 | 82.57 | 82.78 |
| 20 | **Malta** | 98.32 | 98.34 | 98.37 | 98.39 | 98.43 | 98.47 | 98.51 | 98.53 | 98.81 | 98.85 | 98.90 | 98.92 |
| 21 | **The Netherlands** | n.d. | 99.30 | 99.40 | 99.40 | 99.40 | 99.40 | 99.43 | 99.45 | 99.50 | 99.50 | 99.50 | 99.52 |
| 22 | **Poland** | 64.20 | 64.60 | 65.60 | 68.70 | 70.30 | 71.40 | 72.60 | 73.59 | 73.67 | 74.12 | 75.00 | 75.38 |
| 23 | **Portugal** | 81.30 | n.d. | 80.00 | 81.00 | 82.00 | 82.00 | 83.00 | 84.00 | 85.82 | 85.00 | n.d. | n.d. |
| 24 | **Romania** | 43.10 | 43.50 | 43.50 | 46.90 | 46.70 | 47.20 | 47.80 | 49.20 | 50.90 | 52.90 | 54.30 | 56.00 |
| 25 | **Slovenia** | 62.60 | 62.60 | 62.60 | 62.60 | 62.60 | 62.60 | 62.60 | 63.53 | 66.51 | 67.78 | 68.02 | 67.43 |
| 26 | **Slovakia** | 59.50 | 60.40 | 61.60 | 62.40 | 63.60 | 64.70 | 65.20 | 66.40 | 67.70 | 68.40 | 69.13 | 69.70 |
| 27 | **Sweden** | 86.00 | 86.00 | 86.00 | 87.00 | 87.00 | 87.00 | 87.00 | 87.00 | 87.00 | 88.00 | 88.00 | n.d. |
| | **EU average** | 75.93 | 80.01 | 77.69 | 79.89 | 78.96 | 80.70 | 79.93 | 81.55 | 80.35 | 82.13 | 81.48 | 81.55 |

n.d.—no data.

It should be underlined that the initial intention of all WWTPs was to realize three basic objectives: wastewater collection, wastewater treatment and treated wastewater disposal [32]. Sewage sludge management is also a significant element of WWTP operation. The management of sewage sludge is particularly important because in the EU there is a ban on landfilling waste for which the heat of combustion is higher than 6 MJ/kg. For many years, sludge was most often disposed of in landfills or in the environment in a pre-stabilized form (e.g., after aerobic, anaerobic or lime stabilization). However, it always poses a significant technical problem due to high hydration and mass, as well as sanitary hazards. Considering the presence of heavy metals and toxic substances in sludge, which limit its direct natural/agricultural use, safe methods of sludge management should be sought. On the other hand, sewage sludge is a valuable source of biogenic compounds (nitrogen, phosphorus), which can be recovered from it in chemical and thermochemical processes. In addition, energy can be obtained from sludge, which can later be used in the closed circuit of the plant. Therefore, sewage sludge management is also an important element of CE implementation in WWTPs [33].

Along with the socio-economic development in the world, as well as attention to environmental issues in recent decades, more attention has been paid to waste management, which can be a valuable source of raw materials [34]. Therefore, WWTPs are currently at the center of interest in the context of various possibilities for recovering raw materials, e.g., phosphorus from the liquid phase of wastewater and from sewage sludge and ashes from municipal sewage sludge incineration. Many activities are undertaken to modernize and build WWTPs that will respond to current and future challenges related to environmental protection (in the case of CE, they will allow the recovery of raw materials from available waste streams). In the further part of this work, the concept of a WWTP consistent with the idea of CE is described.

### *3.3. Wastewater Treatment Plant of the Future*

The three areas of CE implementation in WWTPs assumed in this research are as follows [35]:

- Water pathway;
- Energy pathway;
- Materials pathway.

The pathways represent the 'nutrients–energy–water' (NEW) paradigm that focuses on technologies for water reuse, resource recovery and energy recovery in water and sewage management. Specific examples for each of the presented pathways in the context of WWTPs are presented in Table 3.

**Table 3.** CE pathways in WWTPs.

| Pathway | Example | References |
|---|---|---|
| Materials pathway | Phosphorus recovery from liquid phase | [36–39] |
| | Phosphorus recovery from sewage sludge | [40,41] |
| | Phosphorus recovery from sewage sludge ash | [42–46] |
| | Nitrogen recovery from liquid phase | [39,47–50] |
| | Nitrogen recovery sewage sludge | [51–55] |
| | Sewage sludge as fertilizer | [56–62] |
| | Sewage sludge as building | [63–66] |
| | Sewage sludge ash as building materials | [67–71] |
| | Bioplastics from liquid phase | [72–74] |
| | Paper/cellulose recovery | [75,76] |
| | Metal and mineral recovery | [77–80] |
| Water pathway | Rainwater harvesting | [81,82] |
| | Reused for agriculture and aquaculture | [83–88] |
| | Reused water for industry | [89–92] |
| Energy pathway | Energy saving at WWTP and distribution systems | [93–96] |
| | Biosolid to energy production (gas, electricity and heat) | [97–101] |
| | Renewable energy | [102–106] |

A conceptual framework for a 'Wastewater Treatment Plant of the Future' focuses on a new look at the municipal wastewater stream as a source of water, energy and secondary raw materials, while maintaining the basic requirements of the WWTP, such as ensuring sanitary safety and optimizing the operating costs of the treatment plant. The general scheme of a WWTP that includes CE approaches in the mentioned three areas (water/energy/raw materials) is presented in Figure 3.

In the water options, a strong emphasis should be placed on sustainable management of water resources, which in the WWTP means not only the above-mentioned water reuse from municipal wastewater for irrigation of soils, but also the optimization of water intake processes [107] and improvement of the water distribution system [108] to reduce water losses in water supply systems as much as possible [109]. In addition, ecological education of society is important, including industrial users of water from the network, because only through the sustainable use of water is it possible to save it at the end-user stage, even before the water turns into wastewater [110]. Water recovery is currently a very important topic in all EU countries. This is mainly due to the need to adapt national legislation to the requirements of water regulation on water reuse for irrigation [111]. Many European countries are increasingly struggling to ensure the continuity of water supplies, and agriculture is already suffering from the shortage of water necessary to irrigate fields. The implementation of an appropriate legal framework, based on already published EC regulations, should allow for the creation of interdependence management structures between wastewater suppliers and reused water users. Currently, water reuse is not widespread in the EU. However, it is worth mentioning that in some Member States, especially those belonging to the Mediterranean basin (such as Spain, France, Greece, Cyprus and Malta), the use of wastewater has clearly increased in recent years and can be expected to be practiced more often. In these countries, there are serious problems related to water stress or water scarcity, which is why technological solutions in the field of water reuse have been developed, as have national guidelines regulating the conditions of water reuse depending on its intended use [17]. There is also a plan to extend the scope of this regulation to reclaimed water intended for further purposes, including reuse for industrial purposes and other indirect uses. The WWTP plays the role of a 'reclamation facility' [20]. This document does not specify the list of technologies that can be used, and WWTPs have discretion here, depending on technical and organizational possibilities, to ensure compliance of physicochemical indicators with the indicated limits. The technologies that can be used for water reuse are in line with advanced treatment methods that have been presented in Figure 2.

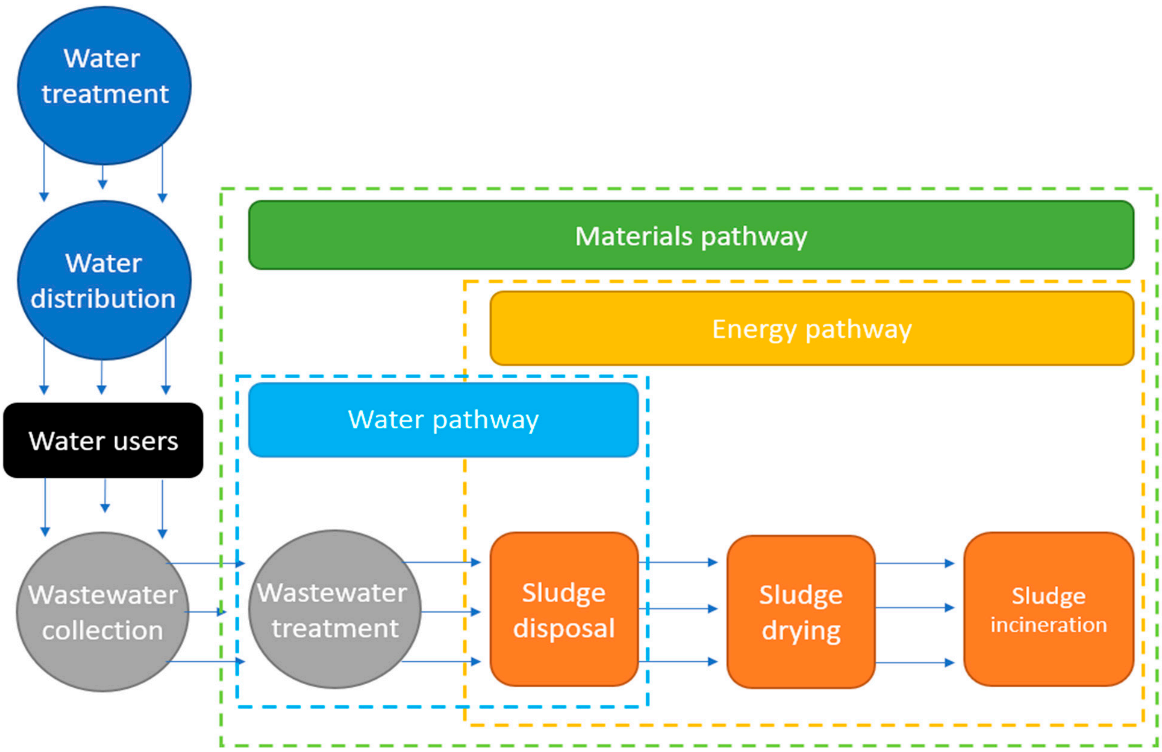


**Figure 3.** A conceptual framework for a CE WWTP.

In the energy pathway, there is also a need to take into account not only energy recovery but also the optimization of energy consumption in WWTPs, e.g., through regulating the efficiency of pumps, blowers and fans [112]. Most WWTPs show a significant environmental and energetic impact due to the large amount of energy consumed in water/wastewater pumping and water losses. The optimization of energy usage could improve energy efficiency and reduce costs and carbon dioxide emissions [113]. Energy input is needed in all stages of WWTP operation, including wastewater collection, all phases of treatment (pre-treatment, primary treatment, secondary treatment and advanced treatment) and disposal and discharge [114]. In a WWTP, it is possible to recover energy from wastewater and sewage sludge. The energy can be recovered in the form of electricity or heat from the following [115]:

- Cogeneration and/or biogas combustion systems;
- Thermal transformation of sewage sludge;
- Chemical oxidation of sewage sludge;
- Heat of treated sewage;
- Other additional installations, such as ground heat pumps and/or photovoltaic panels.

The energy produced in WWTPs can be returned to circulation in a given plant (for the purposes of subsequent cleaning and maintenance processes of the plant), or in the case of production of surplus energy, it can also be sent to a public power grid. The usage of a biogas engine contributes to the production of waste heat from the engine cooling system as well as heat from the exhaust gas system. This heat could be transferred in the engine cooling water stream and further used for heating purposes [115]. There is a possibility to produce both electricity and heat [94]. The energy recovery system from technological installations could contribute to an increase in the energy independence of the WWTP. There is a possibility to recover biogas from wastewater and sewage sludge in the WWTP [116]. Biogas recovery in WWTPs is a well-established technological process [117]. However, while biogas production processes from agricultural and animal waste are popular in developing countries, their application in WWTPs is still limited [118]. There is a significant added value of biogas production in WWTPs—biogas generated in a digester via anaerobic digestion (AD) shows an energy potential of 6.5 kWh/m$^3$ (with 65% methane content), and it could be the main energy source in a given WWTP. Moreover, WWTPs with sludge digestion reduce energy intake and consume about 40% less net energy than WWTPs without AD digestion [119]. There is also a possibility to recover energy during sludge incinerations in WWTPs equipped with sewage sludge incineration installations, e.g., in Germany [120] and Poland [121]. This solution not only allows the use of recovered energy in the plant, but also solves the problem of managing large volumes of sewage sludge (by incineration reducing the volume by approx. 80%). Energy recovery is strongly recommended in WWTPs [122]. It is still a new direction of development and improvement of the energy balance of such plants because neither WWTPs nor water supply companies are treated as energy companies. Their demand for energy is extremely high, so this could bring not only environmental but also economic benefits.

In the materials pathway, the most promising solution is the recovery of nutrients from waste generated in WWTPs [123]. The other materials that can be recovered in WWTPs are various polymers, including cellulose, extracellular polymeric substances (EPSs) and microplastics [124]. Most attention in recent years was devoted to the recovery of phosphorus from waste in WWTPs. This was dictated by the EC recommendations in the field of sustainable management, which have been in force since 2013 [125]. In subsequent years, CE packages supported the development of P recovery technologies from the liquid phase, sludge and ashes in WWTPs [126]. The lowest efficiency is for recovery of P from the liquid phase, due to the low concentration of P in this substrate compared to solid particles (sludges and ashes) [127]. High P recovery can be obtained by chemical treatment of sludge, reaching even 60%. Here, an interesting solution is the deliberate precipitation of struvite, which is a technological problem in conventional WWTPs (deposition of struvite sediment in installations). There is also possible recovery of P from ashes (highest efficiency, up to 100%) via chemical or thermochemical processes that increase P bioavailability in solids. A detailed inventory of P recovery technologies has been presented in a previous paper [128]. The nutrient-rich waste (e.g., biosolids in WWTPs) could be also applied on land, which is one of the oldest methods of usage of WWTP by-products as fertilizers [129]. Sewage rich in P could be spread on the soil surface or injected into the soil. There are requirements in this area, as biosolids before application should be treated at a WWTP with the following process: anaerobic/aerobic digestion, drying, composting, or chemical treatment. It is worth noticing that after thermal treatment, sewage sludge is free of microbiological contamination, and in some countries, such as Germany, it can be directly used in agriculture. It should also be emphasized that untreated sewage sludge should not be used in agriculture, as it may lead to contamination of the soil with pathogenic microorganisms, as well as heavy metals and other impurities contained in the sludge. Currently, land application of sludge is widely practiced in EU countries [119].

The presented data can be applied in future research of various experts that are working in the area of energy efficiency, raw materials efficiency and water management, as part of creating organizational innovations in WWTPs, technological innovations and adaptation to rapidly changing legal requirements and the need for active participation in the process of transformation towards CE.

There are several objectives and needs that have to be met by implementing CE solutions in WWTPs [130]:

- Technological needs: improvement of the efficiency of the wastewater treatment process through modern solutions allowing for a better quality of treated wastewater, reduction in operating costs through the development of technologies for energy recovery and reduction in energy consumption of technological processes and devices, comprehensive approach to wastewater treatment as an opportunity to obtain renewable raw materials, e.g., production of organic fertilizers;
- Social needs: improvement of society's living conditions due to the developed water and sewage management system, much less nuisance in WWTP operation in relation to the immediate surroundings, creation of modern infrastructure, generation of new specialized jobs, creation of new raw materials for use by society;
- Ecological needs: reducing GHG emissions, reducing the amount of energy used from non-renewable sources, minimizing the amount of waste by reusing recovered raw materials, saving drinking water resources, limiting the emission of micropollutants to the aquatic environment;
- Research, development and commercial potential: development of national contractors from the construction sector and increasing export opportunities of the developed technology understood as a product, as well as possible export of economic solutions regarding wastewater treatment installations.

In summary, in the innovative WWTP, special emphasis is placed on technologies aimed primarily at the management of treated wastewater (water renewal and reuse); reduction in the loss of materials, including nutrients and their contamination of aquatic environments (nutrient recovery); removal of micropollutants from wastewater; and effective management of the generated sewage sludge. The implementation of those CE innovations could indirectly contribute to satisfying significant technological, social and environmental needs of the current and future generations, which is in line with sustainability principles [131].

The further development of the circular economy concept in WWTPs is expected in the coming years. There is a strong recommendation to implement innovations, not only in technology but also organization, in new methods of financing investments and WWTP operation, as well as new business models. Currently, treatment plant operators face many challenges in the field of CE implementation, so the results of this work are extremely important for potential CE investments in these plants.

## 4. Conclusions

The transformation toward the CE model covers all sectors of the economy, including the water and wastewater sector. The most important players in the water and wastewater sector are WWTPs, which are responsible for supplying water to the population and for sewage treatment plants. However, due to the progressing climate changes, as well as the need to achieve the security of raw materials (especially in terms of access to water, energy and such raw materials as nutrients), there is an urgent need to expand the activities of these plants. The innovative approach for WWTPs is to turn them into 'resource facilities' that could be so-called 'wastewater treatment plants of the future'. They aim to apply the

CE assumptions in the area of water, energy and raw materials management. There are several studies and documents that deal with these elements in WWTPs. The possible recovery options in WWTPs have been quite well known for many years in European countries. However, their potential is not fully exploited, and there is still a significant necessity to implement technologies that improve the circular management of water, energy and nutrients in WWTPs. One of the driving forces is the development and implementation of the required policy framework and institutional/regulatory frameworks to promote the CE transition. Moreover, innovations, not only in technology but also in new methods of financing investments, as well as new business models, are strongly recommended. Further development of the CE concept in wastewater treatment plants is expected in the coming years.

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## Abbreviations

| | |
|---|---|
| AD | anaerobic digestion |
| BREFs | Best Available Techniques reference documents |
| CE | circular economy |
| CRM | critical raw material |
| EGD | European Green Deal |
| EPS | extracellular polymeric substance |
| ESPP | European Sustainable Phosphorus Platform |
| GHG | greenhouse gas |
| INMAP | Integrated Nutrient Management Action Plan |
| NEW | nutrients–energy–water |
| NF | nanofiltration |
| P | phosphorus |
| RO | reverse osmosis |
| SD | sustainable development |
| SS | sewage sludge |
| SSA | sewage sludge ash |
| UF | ultrafiltration |
| UWWTD | urban waste water treatment |
| WW | wastewater |
| WWTP | wastewater treatment plant |

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