DOI: 10.15199/17.2025.3.3

Key Aspects of Wastewater Treatment Plant Transformation Towards a Circular Operating Model

Kluczowe Aspekty Transformacji Modelu Operacyjnego Oczyszczalni Ścieków w Kierunku Obiegu Zamkniętego

Elena Neverova-Dziopak, Józef Dziopak, Zbigniew Kowalewski*)

Keywords: *wastewater treatment plants, circularity, raw materials, simulation models*

Abstract

Water management is one of the strategic economy sector of any country intended for water resources use and protection and require the operational and effective management system. Business-as-usual approach have shown its insolvency and inability to achieve sustainable performance of water sector in global and local scale. In connection with this, there is an urgent need for a paradigm shift in the development of management strategy. The need for transformation from a prevailing linear strategy to a circular one is driven to a significant extent by increasing water scarcity and the depletion of mineral and energy resources. The municipal wastewater treatment plants (WWTPs) can be an important part of circular sustainability due to integration of energy production, resource recovery and clean water production. Wastewater and sewage sludge can be reused to boost the scarce resources and to optimize the future investments in water and wastewater sector. The transformation of WWTPs have to be based on holistic approach assuming political economic, environmental and social aspects, but the optimal recovery technology is a prerequisite for the implementation of circular economy (CE) solutions. Water-and-resource efficient technologies based on 3Rs approach (Reduce, Replace and Reuse) should be adopted in the initial stage of planning and designing of WWTPs. One of the efficient decision-support tool for optimization of WWTPs designing and modernization towards circular operation&managing is the simulation models, allowing to assess WWTP's recovery potential and profitability of the planned investments.

Słowa kluczowe: *oczyszczalnie ścieków, gospodarka o obiegu zamkniętym, surowce, modele symulacyjne*

Streszczenie

Gospodarka wodna jest jednym ze strategicznych sektorów gospodarki każdego kraju, przeznaczonym do wykorzystania i ochrony zasobów wodnych i wymaga operacyjnego i skutecznego systemu zarządzania. Podejście typu business-as-usual okazało się nieefektywnym i nie prowadzi do osiągnięcia zrównoważonego rozwoju sektora wodnego w skali globalnej i lokalnej. W związku z tym istnieje pilna potrzeba zmiany paradygmatów w strategiach jej zarządzania. Potrzeba transformacji dominującego obecnie modelu liniowego na strategie obiegu zamkniętego jest w znacznym stopniu napędzana rosnącym niedoborem wody i wyczerpywaniem się zasobów mineralnych i energetycznych. Miejskie oczyszczalnie ścieków (WWTP) mogą być ważną częścią zrównoważonego rozwoju ze względu na integrację produkcji energii, czystej wody i odzyskiwania zasobów. Ścieki i osady ściekowe mogą być ponownie wykorzystywane w celu zwiększenia ograniczonych zasobów i optymalizacji przyszłych inwestycji w sektorze wodno-ściekowym. Transformacja oczyszczalni ścieków musi opierać się na holistycznym podejściu uwzględniającym aspekty polityczno-ekonomiczne, środowiskowe i społeczne, a optymalna technologia odzyskiwania jest warunkiem wstępnym wdrożenia rozwiązań gospodarki o obiegu zamkniętym (CE). Technologie oparte na zasadach zamkniętego obiegu wody i zasobów (tzw. podejście 3R: Reduce, Replace and Reuse) powinny być uwzględniane na początkowym etapie planowania i projektowania oczyszczalni ścieków. Jednym z efektywnych narzędzi wspomagających podejmowanie decyzji w celu optymalizacji projektowania i modernizacji oczyszczalni ścieków w kierunku gospodarki o obiegu zamkniętym i zarządzania nimi są modele symulacyjne, pozwalające ocenić potencjał odzysku oczyszczalni ścieków i rentowność planowanych inwestycji. Wybrane przykłady ich zastosowania są przedstawione w artykule.

1. Topicality of the problem

Population increase and economic growth caused significant increase of water consumption. As a result, 36% of the world's population already lives in water-scarce regions (Rodriguez et al. 2020). Climate change may worsen the situation. For the third year in a row, the World Economic Forum has included the water crisis in its top three global risks (World Economic Forum 2022; UN 2017a).

Unsustainable approach and inadequate water resource management leads to loss of ecological, economic and social benefits. Sustainable water management is a critical condition for achieving the Sustainable Development Goals, especially Goal number 6: "Ensure availability and sustainable management of water and sanitation for all"(UN Water 2016). The achievement of Goal number 6 is directly related to the pursuit of Goal number 15, which involves the protection of aquatic ecosystems and prevention of water borne

---

* **Elena Neverova-Dziopak,** Department of Environmental Management and Protection, Faculty of Geo-Data Science, Geodesy, and Environmental Engineering, AGH University of Krakow, al. Mickiewicza 30, 30-059 Kraków, Poland, https://orcid.org/0000-0002-4665-0928; **Józef Dziopak**, Department of Infrastructure and Water Management, Faculty of Civil and Environment Engineering and Architecture, Rzeszow University of Technology, al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland, https://orcid.org/0000-0001-7985-5797; **Zbigniew Kowalewski** (corresponding author), Department of Environmental Management and Protection, Faculty of Geo-Data Science, Geodesy, and Environmental Engineering, AGH University of Krakow, al. Mickiewicza 30, 30-059 Kraków, Poland

diseases. According to the World Health Organization (WHO), these goals of sustainability cannot be achieved without treating wastewater before the discharge into surface waters to protect the environment and public health (Kumar, Bilal, and Ferreira 2022). Thus, there is an urgent need to develop the cost-effective integrated wastewater treatment and recovery technologies or to optimize existing ones to ensure the ecological safety of aquatic ecosystems and achieve environmental sustainability (Varjani, Pandey, and Upasani 2020). One of the main objective of the International Decade for Action "Water for Sustainable Development" is the "integrated management of water resources for achievement of social, economic and environmental objectives"(UN 2017a).

Water management is a strategic economy sector of any state, embraces a large number of natural water resources and complex system of technical infrastructure objects, de-signed to provide the population and industries with water, to treat wastewater in order to protect all types of waters and to prevent or mitigate the other harmful impacts. Such an extremely complex multi-component natural-technical system requires an integrated effectively operating water management system aimed at optimizing water use and minimizing the impact on the environment. This can only be ensured by a change in paradigms and business-models.

The need of transition from a prevailing linear strategy to a circular one is driven to a significant extent by water crisis and the depletion of mineral and energy resources. This development has two main drivers: general process improvements and the contribution to the recycling of resources (van Loosdrecht and Brdjanovic 2014).

One of the key advantages of implementing of circular economy assumptions in wastewater treatment technologies is the valuable resource recovery and reuse, that could transform wastewater transport and treatment services from very expensive to a self-sustaining and value-adding system (Rodriguez et al. 2020). Between 50 and 100% of lost waste resources are contained in wastewater (House 2012).

"In a world where demands for freshwater are continuously growing, and where limited water resources are increasingly stressed by over-abstraction, pollution growth and climate change, neglecting the opportunities arising from improved wastewater management is nothing less than unthinkable in the context of a circular economy" (UN 2017b).

The municipal wastewater treatment plants (WWTPs) can be an important part of circular sustainability due to integration of energy production, resource and water recovery. Wastewater and sewage sludge can be reused to boost the depleting natural resources and to increase the efficiency of future investments in water and wastewater sector (Fig.1).

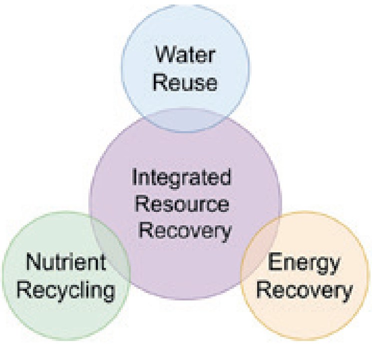

Fig. 1. Integrated resource recovery including water reuse, nutrient recycling and energy recovery (Cornejo 2015)

Rys. 1. Zintegrowane odzyskiwanie zasobów, w tym wtórne wykorzystanie wody, recykling substancji biogennych i odzyskiwanie energii (Cornejo 2015)

However, nowadays cities are not considered sustainable because they do not (re)use resources efficiently. An important paradigm shift is necessary at multiple levels to transform the Wastewater Treatment Plants (WWTP) operating according to Linear Economy Model (TAKE-MAKE-USE-DISPOSE) and advance of sustainable sanitation services toward a Circular Economy Model, in which WWTP is considered as the Water and Resource Recovery Facilities (WRRF) operating according to Circular Economy Model (REDUCE-REUSE-RECYCLE) (Fig 2).

Circular economy is a tool to achieve the sustainable development goal nr 6 in the area of water and sanitation by providing and ensuring overall access to water supply and sanitary systems by 2030, implementing the sustainable management of water and sanitation objects and systems by means of the following actions (UN 2022) :

- ensure universal and equitable access to safe and drinking water for an affordable price for all people on the planet;
- ensure access for all to adequate and equitable sanitary and hygienic conditions and eliminate open defecation, paying particular attention to the needs of all social groups and those in vulnerable situation;
- improve water quality by reducing pollution and halving the amount of un-treated wastewater discharge and significantly increasing the recycling and safe reuse of resources globally;
- decisively increase water-use efficiency in all sectors of economy, ensure universal and equitable access to safe and drinking water for an affordable price for all people on the planet;

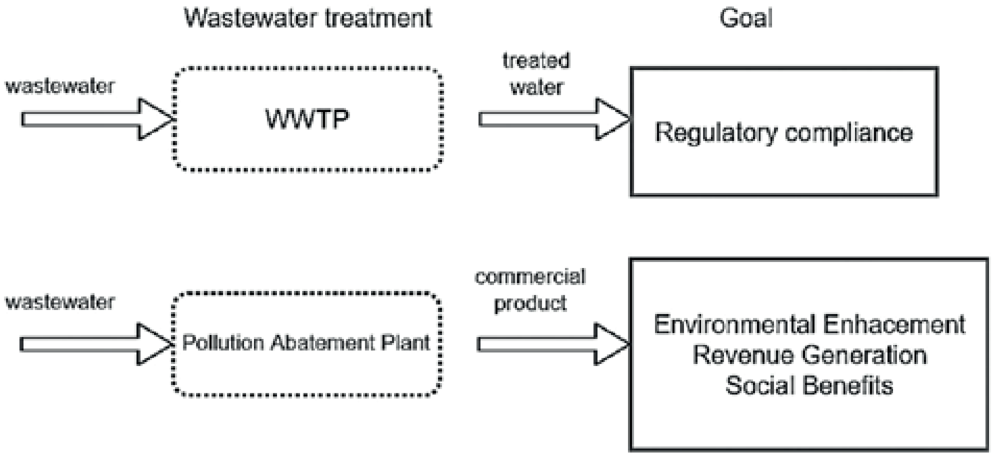

Fig. 2. WWTP operation principle vs WRRF operation principle (WEF 2014)

Rys. 2. Zasada działania oczyszczalni ścieków w porównaniu z zasadą działania urządzeń do odzyskiwania wody i zasobów (WEF 2014)

- ensure access for all to adequate and equitable sanitary and hygienic conditions and eliminate open defecation, paying particular attention to the needs of all social groups and those in vulnerable situation;
- improve water quality by reducing pollution and halving the amount of untreated wastewater discharge and significantly increasing the recycling and safe reuse of resources globally;
- decisively increase water-use efficiency in all sectors of economy, ensure sustainable withdrawals and freshwater supply to mitigate water scarcity and substantially reduce the number of people afflicted by water scarcity;
- implement integrated and efficient water resources management at all levels, including transboundary cooperation as appropriate;
- expand international cooperation and support to developing countries in improvement of water-and sanitation-related activities and undertaking, including water acquisition and storage, sea water desalination, increasing water use efficiency, wastewater treatment, recycling and reuse technologies, withdrawals and freshwater supply to mitigate water scarcity and substantially reduce the number of people afflicted by water scarcity;
- implement integrated and efficient water resources management at all levels, including transboundary cooperation as appropriate;
- expand international cooperation and support to developing countries in improvement of water-and sanitation-related activities and undertaking, including water acquisition and storage, sea water desalination, increasing water use efficiency, wastewater treatment, recycling and reuse technologies.

Today, the introduction of the principles of the circular economy in the water sector seems timely, relevant and practical option for the achieving of the above mentioned sustainable development goals.

2. WWTP Recovery Potential

Wastewater Treatment Plants have great potential to improve water treatment processes in order to reduce the amount of treated wastewater and carrying out the recovery of potential resources from wastewater sludge, such as nutrients (phosphorus, nitrogen), energy and water (Diaz-Elsayed et al. 2019; I. Pikaar et al. 2022; van Leeuwen et al. 2018).

According to Food and Agriculture Organization of the United Nations (FAO 2022)) 312 million megaliters (ML) of municipal wastewater is produced annually, of which 187 million ML is treated, equaling to about 60% of the total. According to UNESCO, currently only 20% of wastewater is properly treated with the formation of about 140 million tons of sewage sludge in dry matter (Kiselev and Magaril 2019; UN 2012).

Electricity needs for water treatment process range from 250 up to 500 kWh/mln m3 of treated wastewater with the prospect of growth by 44% by 2030, especially for countries outside the Organization for Economic Co-operation and Development (OECD(UN 2016).

Water is the dominant component of wastewater with typically more than 99% of municipal wastewater comprised of water itself and 1% of suspended, colloidal and dissolved matter (biodegradable organics, plant nutrients, pathogenic microorganism, heavy metals, synthetic organic pollutants, micro-pollutants e.g. medicines, cosmetics, cleaning agents, plastic). The main parameters of raw wastewater quality and sewage sludge are presented in Table 1 (I. Pikaar et al., n.d.) and Table 2 (Tchobanoglous, Burton, and David Stensel 2014).

Table 1. Typical composition of raw municipal wastewater (I. Pikaar et al., n.d.)

Tabela 1. Typowy skład surowych ścieków komunalnych (I. Pikaar i in., n.d.)

Parameter	Low strength	Medium strength	High strength
COD total (mg/L)	500	750	1200
BOD5 (mg/L)	230	350	560
Volatile fatty acid (VFA) (mg-acetate/L)	10	30	80
Total nitrogen (mg/L)	30	60	100
Total phosphate (mg/L)	6	15	25
Total suspended solids (TSS) (mg/L)	250	400	600

Table 2. Typical composition of raw municipal sewage sludge (Tchobanoglous, Burton and David Stensel 2014)

Tabela 2. Typowy skład surowych osadów ściekowych komunalnych (Tchobanoglous, Burton i David Stensel 2014)

Parameter	Primary sludge	Secondary sludge
Total solids (TS) (%)	5–9	0.8–1.2
Nitrogen (%TS	1.5-4.0	0.8–1.2
Phosphorus (%TS)	0.8–2.8	0.5-0.7
Potash (K_2O %TS)	0-1.0	0.5–0.7
Cellulose (%TS)	8-15	7–9.7
Iron (g Fe/kg)	2–4	-
Silica (SiO_2%)	15–20	-
Grease and fats (%TS)	7–35	5-12
Protein (%TS)	20-30	32–41
Organic acids (mg/L as acetate)	200-2000	1100–1700
Energy content (MJ/kg TS)	23–29	19-23

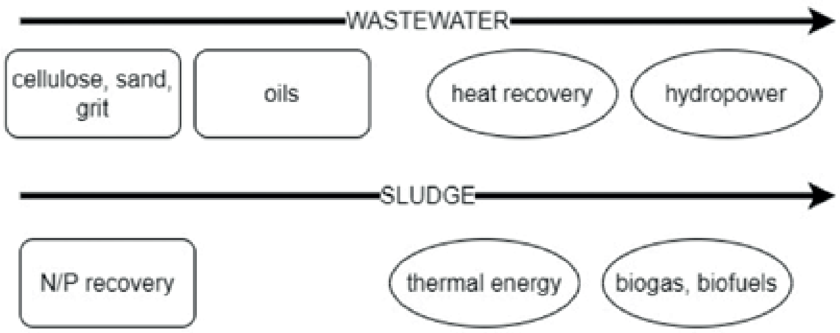

Fig. 3. Resource recovery possibilities (Papa et al. 2017)

Rys. 3. Możliwości odzyskiwania zasobów (Papa i in. 2017)

Along with municipal wastewater, industrial wastewater has a high potential for resource recovery including nutrients, energy, chemical compounds, organic matter, metals, and water itself. The potential resources which can be recovered from WWTP are presented at Fig.3.

There is a huge untapped potential for recovering valuable resources from wastewater treatment plants (Tab.3).

Table 3. Possible application of basic resources recovered from wastewater and sludge

Tabela 3. Możliwe sposoby zastosowania podstawowych zasobów odzyskanych ze ścieków i osadów

Type of resource	Application possibility
Water	Irrigation, non-potable domestic use, industrial use, direct&indirect potable domestic use
Sand	Construction industry
Cellulose	Biochemical industry, construction industry, paper&pulp industry
Biosolids	Agriculture, construction industry
Volatile fatty acids	Biochemical industry, bioplastic, agriculture
Energy (biogas, thermal)	Energy production, heating/cooling purposes
Nitrogen	Agriculture
Phosphorus	Agriculture
Metals	Metallurgical, galvanic, electronic industry

The benefits of recovered resource application in different sectors are shown in Fig. 4.

3. New challenges

The municipal wastewater treatment plants (WWTPs) can be one of the priority fac-tors and important part of circular sustainability due to integration of energy production, valuable resource recovery and water production for different types of use. WWTPs in the near future are to become "ecologically sustainable" technological systems. Unfortunately most of conventional WWTPs now primarily focused on the pollutants removal rather than the recovery of valuable resources. Sustainable WRRF systems remains a significant challenge due to numerous organizational, legislative, financial and other barriers (Yadav et al. 2021).

Transformation of traditional WWTP into WRRF is connected with great changes moving away from costly energy-intensive wastewater treatment towards energy-saving, sustainable technologies ensuring improvement of the energy balance of operation and resource recovery (Regmi et al. 2019). One of the basic way to reduce sewage sludge amount and the utilization of sludge chemical components and energy content is the converting sludge from costs to benefits (Fig. 5).

This shift will require new research, advanced treatment technologies and infrastructure and must be guided by the application of green engineering principles to ensure economic, social, and environmental sustainability

The existing wastewater treatment technologies have different potential for nutrients, water, and energy recovery, therefore they differ in terms of technological feasibility and economic profitability. As noted by the authors of (Puyol et al. 2017), there are a broad range of recovery strategies available, with further differentiation based on product (Fig. 6).

The development of technologies and processes for resource treatment and recovery give great possibilities for elaborating the new technological trains or modifying and optimizing the existing ones (Fernández-Arévalo, Lizarralde, Fdz-Polanco, et al. 2017).

However, the decision-making about the choice of an appropriate technological pattern and raw material recovery pro-

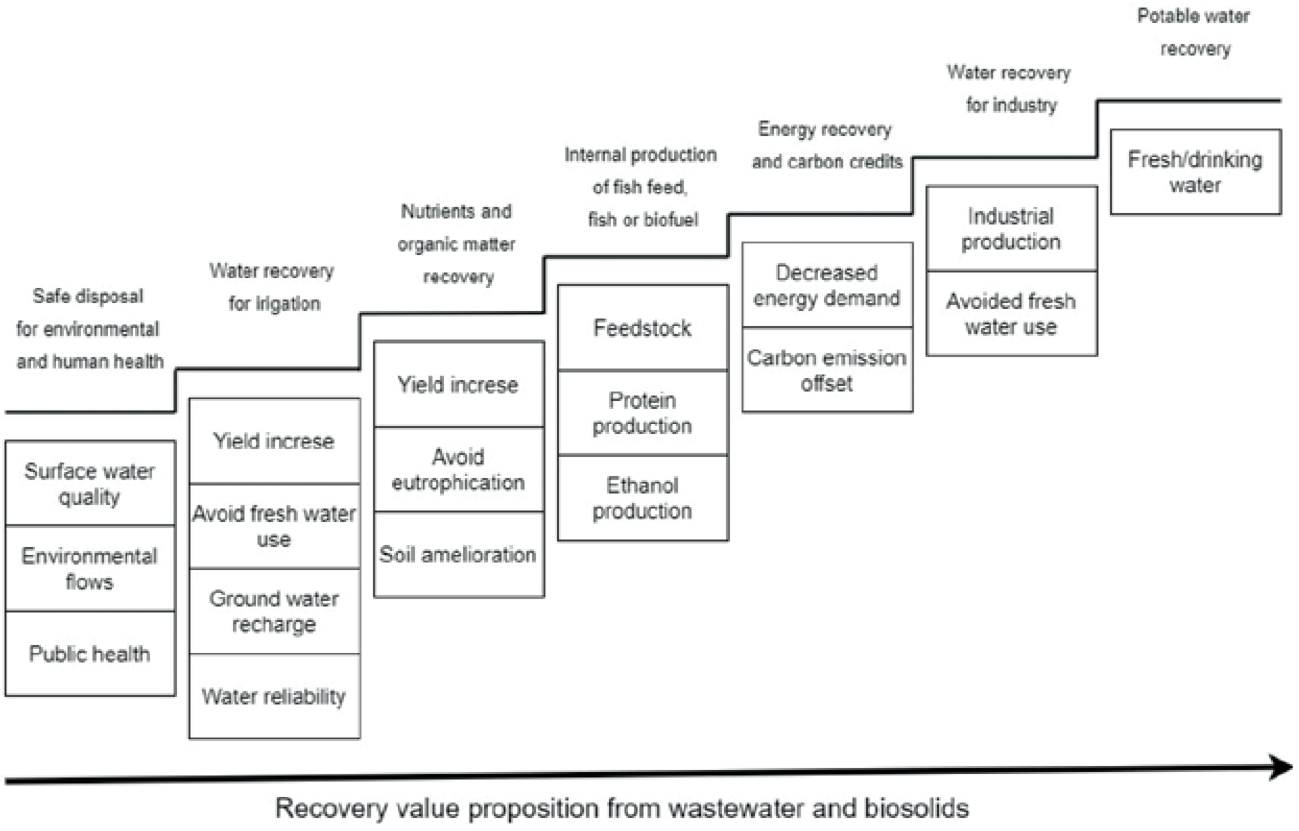

Fig. 4. The reuse value chain (Drechsel, Mahjoub, and Keraita 2015)

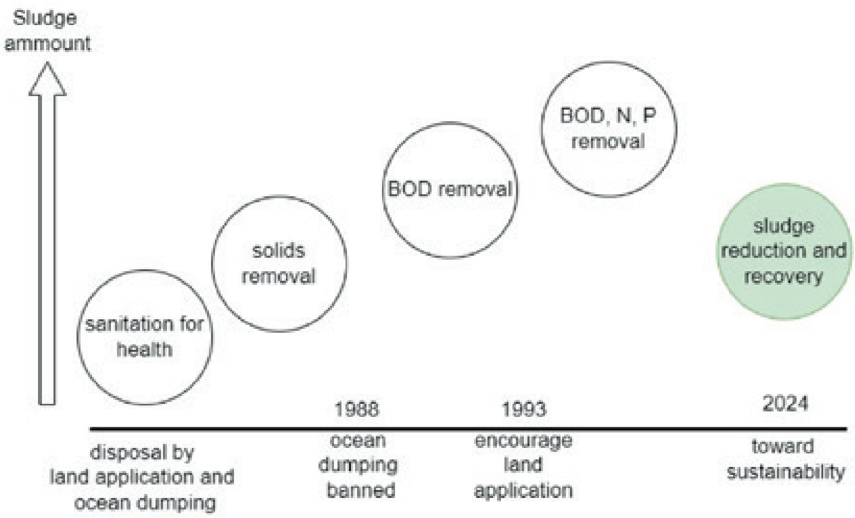

Fig. 5. The change in the arc of sludge disposal history (Peccia and Westerhoff 2015)
Rys. 5. Zmiany historyczne w postepowaniu z osadami (Peccia i Westerhoff 2015)

cesses is conditioned by the need to analyze its profitability which is a difficult and sometimes ambiguous decision. Comprehensive and refined analysis of different plant technological trains are the basic aspects in decision-making from an energy and resource recovery perspective.

Currently, there is a real lack of analysis of existing wastewater treatment plants upgrading effects for accommodation the concept of resource recovery (Marleni, Putri, and Istiqomah 2020).

More than 600 European WWTP plants were investigated, representing a treated capacity load equivalent to 20 million population, which demonstrated that resource recovery operations from wastewater and sewage sludge is just in its infancy stage: only 40% of plants perform at least one option for material/energy recovery. The production of energy from biogas occurs frequently but only in large plants with high throughput. On the other hand, some well-known for a long time options, such as external reuse of treated effluent or nutrients recovery, were implemented only in a minority of plants (Papa et al. 2017).

Regenerative methods solve two problems: wastewater treatment and recovery of valuable substances, that can demand the use of more complex methods and technologies. The selection of appropriate treatment methods is a prerequisite for the efficient removal of pollutants and the recovery of raw materials. Wastewater treatment methods, the possibility of recovery and utilization of valuable substances should be justified in terms of technological and economic conditions, taking into account the legal environmental demands and local conditions. Ultimately, the cost of building treatment facilities, the efficiency and reliability of their operation, the protection of the wastewater recipient from pollution depend on this decision. The possibility of extracting and utilizing valuable substances from wastewater and, consequently, increasing the profitability of WWTP operation also depends on the solution of this issue.

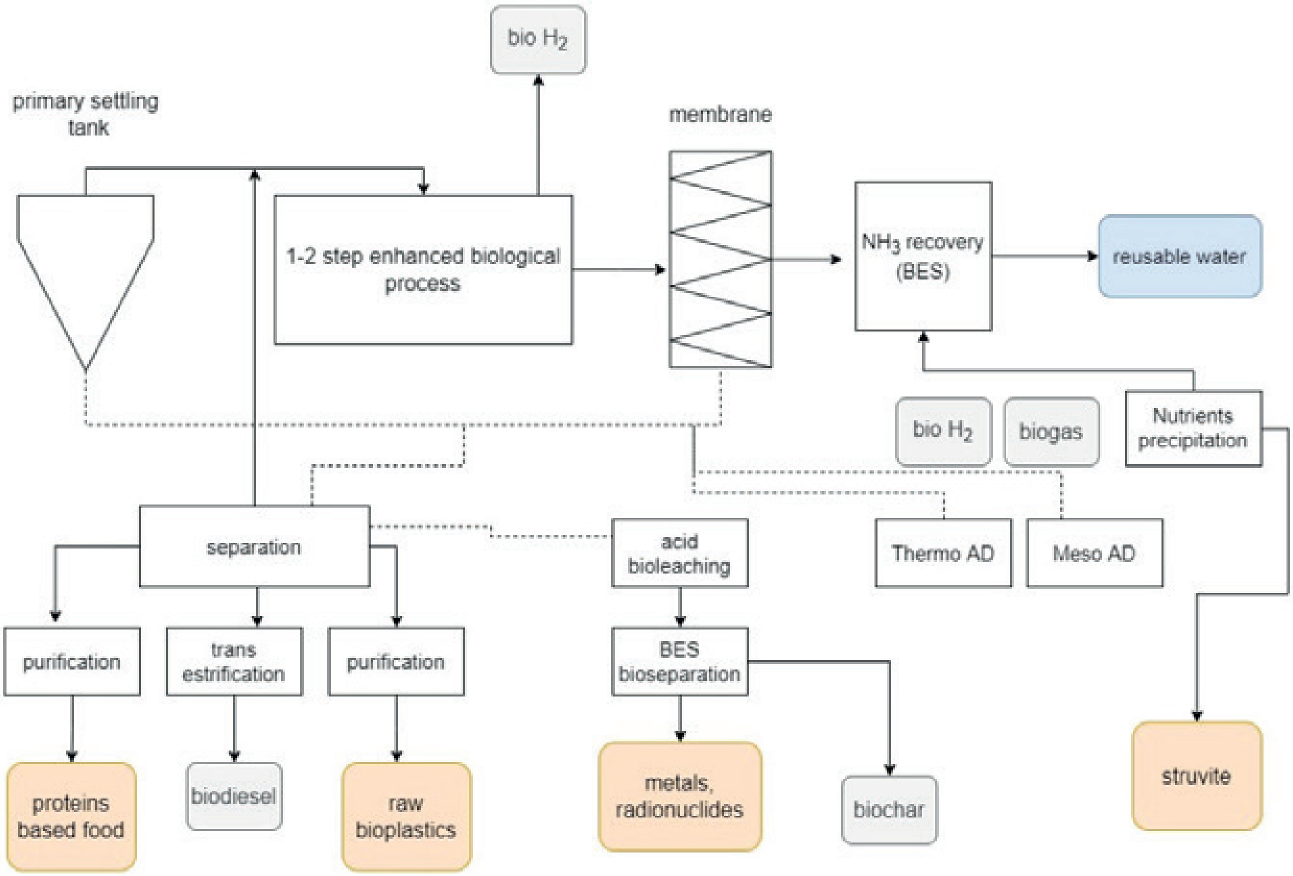

Fig 6. Conceptual overview of different biological technologies applied in wastewater treatment for energy and resource recovery (Kroiss 2004)
Rys. 6. Przegląd koncepcji różnych technologii biologicznego oczyszczania stosowanych w celu odzyskiwania energii i zasobów (Kroiss 2004)

4. The role of simulation models

Model is a simplified similarity of a real object that reflects essential features (properties) of the real object under study and meet the purpose of modelling.

A mathematical model is an approximate description of definite class of phenomena expressed in mathematical symbols and patterns. Computer models have become a common tool for mathematical modeling and are used to solve scientific and applied tasks in various fields. Such models are used to obtain new knowledge about an object or to approximate the behavior of systems that are too complex for analytical study.

There are analytical and simulation modeling. In analytical modeling, abstract mathematical models of a real object are studied in the form of algebraic, differential and other equations, as well as those involving the implementation of an unambiguous computational procedure that leads to their precise solution. In simulation modeling, mathematical models are studied in the form of an algorithm(s) that reproduces the functioning of the system under study by sequentially performing a large number of elementary operations (Fishwick 1995; Sokolowski and Banks, n.d.).

Since the natural experiment performance in WWTP conditions is not possible, the significance of mathematical modelling and simulation research as an efficient instrument of decision-making becomes very important.

In past few decades many simulation models for designing and optimizing of wastewater treatment plants were elaborated. New paradigm of circular economy in wastewater management forces the necessity of establishing the simulation tools to address new challenges: protection of water resources and the environment, energy reduction and production, and resource recovery potential assessment (Arnell et al. 2017). Therefore, the conventional mathematical models used in need to be updated.

The resource recovery perspective should be applied to new individual processes, technologies and plant arrangement. The number and level of models developed to date give an overview of the complexity of the treatment plant configurations and provide a wide range of possibilities and technological process combinations in order to construct the optimal technological trains ensuring WWTPs "circularity" (Fernández-Arévalo, Lizarralde, Maiza, et al. 2017).

Models have demonstrated their suitability for WWTP operational optimization purposes and increasing their efficiency to achieve better effluent quality at lower costs. They also constitute a useful tool to support the transition of WWTPs into WRRFs that maximize the valorization of resources recovered from wastewater and sewage sludge (Solon et al. 2019).

In this regard, the plant-wide modelling (PWM) library is a complete model library that includes conventional and advanced treatment technologies that allows economic and energetic analyses to be carried out in a comprehensive manner.

5. A review of simulation models

In the model review, only engineering programs for modeling the operation of wastewater treatment plants were taken into account, in which precipitates modeling is a kind of addition to the basic program functionalities. The review does not include dedicated chemistry programs such as Aspen or PHREEQC model families, MINTEQ, MINTEQA2, MINEQL þ , CHEMEQL V.2.0 and AQUASIM 2.0 (Natividad Marin, Burns, and Schneider 2023). In the case of implementing circular economy elements at WWTP, the most convenient way is to use simulation programs with built-in operating models. There are a number of software supporting the process of modeling, both the operation of wastewater treatment plants and raw materials recovery. Commercial programs with a graphical interface include: GPS-X, SIMBA, BioWIN and WEST. There are also non-commercial solutions: STOAT, ASIM, AQUASIM.

BioWIN is a product from Envirosim. In the field of biological wastewater treatment, the family of ASM models is used, and the ASDM model is responsible for sludge management (Envirosim, n.d.).

Precipitation modeling is an additional function of these software. More importantly, for the modeling of crystalline phosphorus compounds, typically chemical (Jia et al. 2017; Xie, Giammar, and Wang 2016) or mathematical MATLAB, Maple, Simulink (Hanhoun et al. 2011; Nair, Haugen, and Ratnaweera 2021; Petzoldt and Moreda 2016; Türker and Çelen 2011) software are used. Occasionally CFD methods are used (Ye et al. 2017), however, they are mainly based on small-scale laboratory experiments. In the field of precipitation modelling, it is possible to model Al and Fe processes mainly as an element of chemical phosphorus removal in the process of the so-called coagulation. In addition, it is possible to include the Spontaneous Chemical Precipitation model where the production of calcium and magnesium compounds is modeled. Struvite, hydroxyapatite (HAP) are formed in these processes, as a mathematical model is used model developed by Musvoto (Musvoto, Wentzel, and Ekama 1999).

In the BioWin program the process of obtaining struvite looks as follows:

- select the ASDM model
- in the model options select MAP struvite, DCPD brushite or HAP apatite modeling
- in the stoichiometry options, the individual components for obtaining struvite, vivianite, brushite and apatite can be adjusted.

The components for vivianite are soluble phosphate, precipitate vivianite, metal soluble ferrous, The components for struvite: N ammonia, soluble phosphate, precipitate struvite, metal soluble magnesium,

The components for brushite: P soluble phosphate, precipitate brushite, metal soluble calcium,

The components for hydroxyapatite: P soluble phosphate, precipitate brushite in minus, precipitate hydroxyapatite,

In scheme (Fig. 7), the excess sludge is first directed to the digester, then to the press, after which NaOH and $MgCl_2$ are added, and it is mixed in a bioreactor. The final facility in which struvite is obtained is a cyclone.

In the case of other substances, there is a need to add Fe, also there is no separate vessels/tanks/reactors (or cyclones) for harvesting the products of this reactions. This type of line is presented at Fig. 8. All four recovered substances could be shown directly in software.

The GPS-X program uses a group of MANTIS models which are also variant models ASM (Faris et al. 2022). This model can simulate the calcium phosphate, magnesium hydrogen phosphate, and ammonium magnesium phosphate crystallization process. Similar to BioWin it also use a model created by Musvoto (Musvoto, Wentzel, and Ekama 1999). According to GPS-X manual reactions of crystallization take a place in some designed

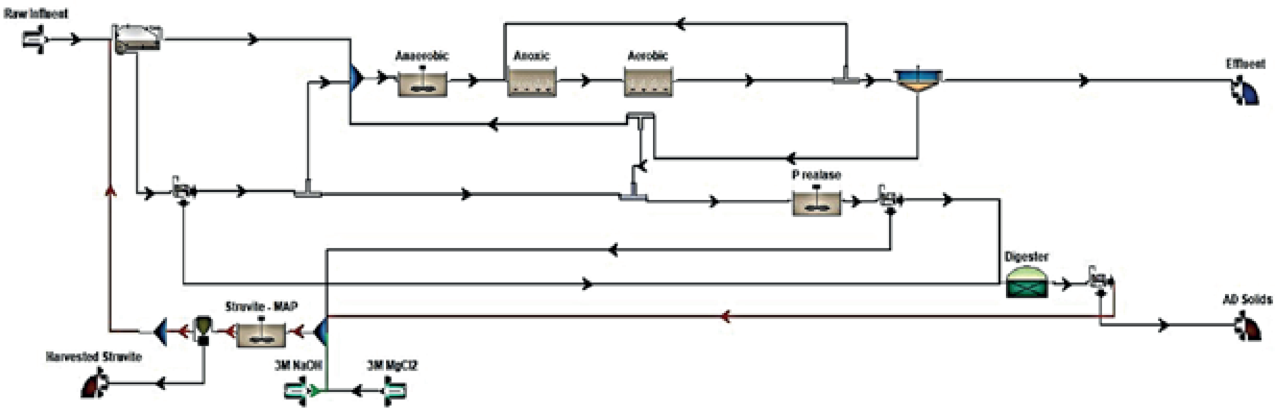

Fig. 7. Struvite recovery line generated with BioWin software

Rys. 7. Linia odzyskiwania struwitu wygenerowana za pomocą oprogramowania BioWin

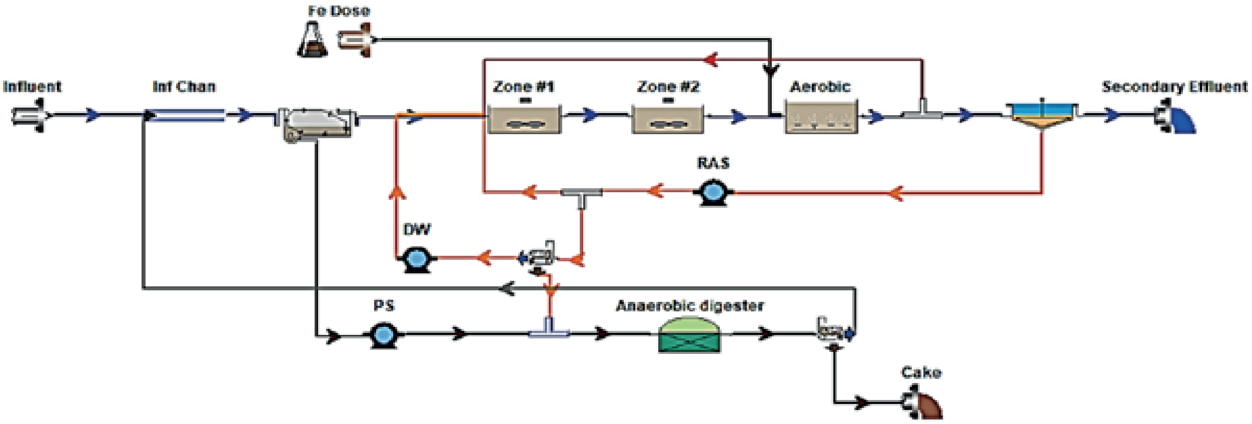

Fig. 8 Typical bruschite recovery line generated with BioWin software

Rys. 8 Typowa linia odzyskiwania bruskitu wygenerowana za pomocą oprogramowania BioWin

conditions. The precipitation of struvite takes place if the Mg^{2+}, NH^{4+} and PO_4^{3} – species are present in the solution. The concentrations of NH^{4+} and PO_4^{3} – are estimated based on pH value of the solution.

Newberyite is precipitate of Mg with phosphate at lower pH. For this precipitate, Mg^{2+} and HPO_4^{2} – ionic species are required. The concentration of HPO_4^{2} – ion is estimated based on pH of the solution.

The struvite precipitation reactor model is realized in granular bed reactor. The most important parameter is velocity of fluidization in reactor moving bed (Hydromantis 2018). Typical struvite harvesting line created in GPS-X is shown at figure 9.

SUMO is a modeling software by Dynamita, once again the basics are in ASM and for precipitation SUME used own created sub-model called Sumo2S. There is a possibility to modelling and monitoring a recovery of amorphous calcium phosphate (ACP), struvite (STR), vivianite (VIVI). Software realize this functions

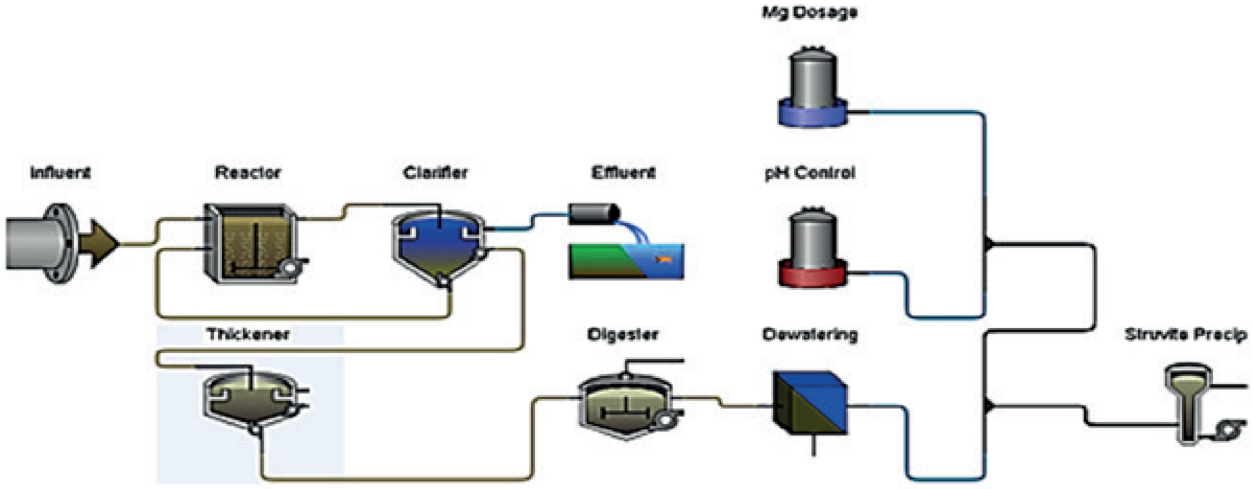

Fig. 9 Typical precipitation line created in GPS-X

Rys. 9 Typowa linia wytrącania utworzona w oprogramowaniu GPS-X

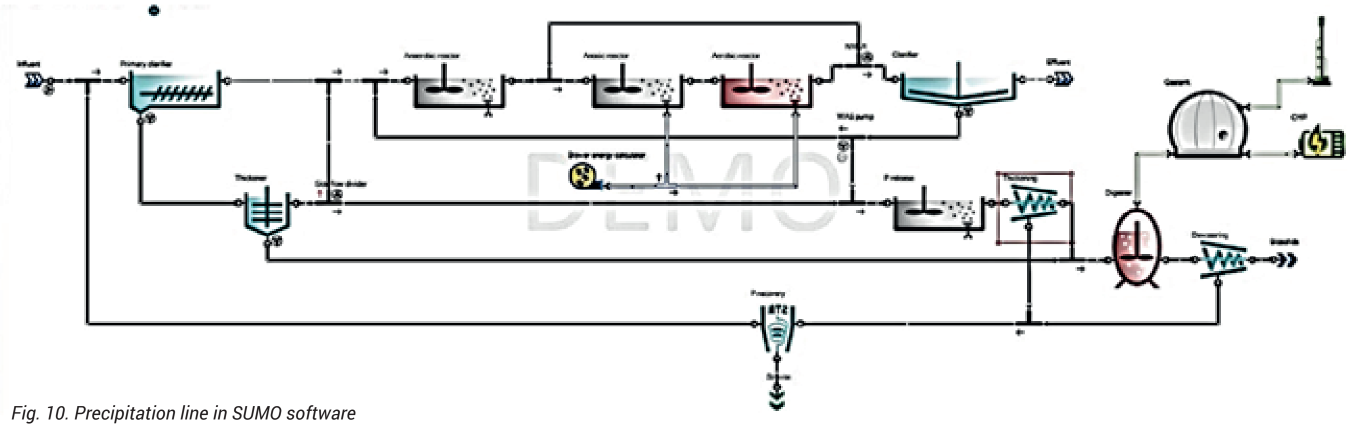

Fig. 10. Precipitation line in SUMO software
Rys. 10. Linia opadów w oprogramowaniu SUMO

as stand-alone elements of existing WWTP line (Dynamita 2020). Sumo2S is also a stoichiometry-kinetic model (Aguiar et al. 2022). A separate line for precipitation in Sumo software is presented on figure 10.

In addition to the empirical approach, there is a statistical approach based mainly on regression models or even on machine learning (Perwitasari et al. 2018; Shalaby et al. 2015).

In order to illustrate the possibility of using simulation tools to assess the potential for the recovery of biogenic substances, a simulation model of struvite recovery was created in the computer programs BioWin version 6.2 and SUMO version 22. A line was modeled consisting of a primary clarifier from which excess sludge is directed to the thickener and then to the P reactor-release (volume 500 m3), and then an aerobic digester (temp. 35 C), thickener and struvit recovery unit.

The biological system consists of an anaerobic reactor (V=1000 m^3, 0 mg O_2/l), an anoxic reactor (V= 1500 m^3, 0.5 mg O_2/l), and an aerobic reactor (V=4500m^3, 2 mg0_2/l). The system ends with a secondary settling tank, with internal recirculation (recirculation level 300%) and external recirculation (recirculation level 100%). The lines created in both programs have identical elements and operating parameters. The BioWin program uses the ASDM model in its basic parameters and fractionation. The SUMO program also uses its own proprietary SUMO model in its basic parameters. Modeled in steady state mode, input parameters are presented in the table 4.

Table 4. Input parameter values
Tabela 4. Wartości parametrów wejściowych

Flow m^3/d	24 000
COD total, mg/l	420
TKN mg/l	34
TP mg/l	4.3
pH	7.2
TSS mg/l	45
Calcium, mg/l	150
Magnesium, mg/l	15

The modeling result was the amount of struvite formed in the precipitation line, which were quite close when using the tested models. In the case of the SUMO model it was 41,100 g TSS/m3, while in the BioWin model it was 43,000 g TSS/m3.

Due to the lack of similar literature data, the authors were not able to compare the results with the results obtained by other authors. The analysis of the experiences of various authors allows to draw conclusion, that a holistic approach to the whole process of wastewater treatment seems to be dominant. The authors are more interested in the whole process, including economic and environmental aspects as resource recovery, than more than verifying the reliability of modeling results (Lin et al. 2016; Nair, Haugen, and Ratnaweera 2021; Puchongkawarin et al. 2015) or additionally as an element of Benchmark Simulation Model no 2 (BSM2) (Flores-Alsina et al. 2021).

The purpose of the presented examples was to show the possibilities of the discussed simulation programs as decision-making support tools regarding the transformation of the linear model of operation of wastewater treatment plants towards a model based on circular economy solutions. Initial diagnostics and assessment of the profitability of applying these or other circulation considerations may be based on forecasts obtained using simulation models for individual technological systems, taking into account local conditions.

Application of models to small scale always yields over 90% of compliance level with laboratory results. In the case of a technical or industrial scale for WWTP operation modeling, the effects are also satisfactory. In the case of AirPrex recovery modelling based on the GPS-X program for EPBR treatment plant more than 95% compliance level was obtained between the model and the actual values of phosphorus compounds concentrations (Yoshida et al. 2019).

GPS-X has also been used for a comprehensive modeling of wastewater treatment and recovery process, along with economic and energy analyses (Duan et al. 2019). Tests performed on a laboratory line in a 10L SBR reactor showed a high compliance between the experimental results and the results of ASAM and WEST simulation programs. Phosphorus precipitation was at the level of 83-91%, while the model results were slightly lower (Tomei et al. 2020). A similar comprehensive approach to struvite recovery process is presented by Morrissey and Shaw (Morrissey et al. 2022; Shaw et al., n.d.).

Comprehensive simulation models that would serve as a tool for the effective transformation of wastewater treatment plants into facilities for water and raw materials production are currently under development. On the other hand, some elements of the circular economy can be successfully implemented based on modifications of the existing traditional simulation models.

Simulation software for modeling the operation of biological wastewater treatment plants is widely distributed and available. The results that these programs generate are highly correlated with real conditions. However, they concern the operation of the treatment plant related to the pollution reduction.

6. Conclusion

One of the key elements of circular economy is the development and implementation of appropriate policies and management strategies in the field of designing and modernization of municipal wastewater treatment plants in order to reduce the negative impact on the environment. Increasingly stringent ecological requirements and standards for treated wastewater and introduction of additional stages of sludge processing often lead to intensification of technological processes and rising energy costs. Currently, it is becoming obvious that the existing WWTP management model, based on the traditional (linear) approach does not allow to fully address the current threats: environmental degradation and depletion of natural resources.

The selection and design of wastewater treatment technology operating in accordance with the closed cycle model, satisfying the environmental, economic and legal requirements with local conditions consideration is a complex multifactorial problem. Evaluation of alternatives can be carried out using simulation models.

The practical application of simulation models creates a powerful, but at the same time a rather simple tool for managers to work towards the transition of wastewater treatment plants to circular economy operating model. Computer models have become a common tool for mathematical modeling and are used to solve scientific and applied tasks in the field of water management. Since the natural experiment performance in WWTP conditions is not possible, the significance of mathematical modelling and simulation research as an efficient tool of decision-making becomes very important.

REFERENCES

[1] Aguiar, Samuel E., Manying Zhang, Adrian Romero-Flores, Tom Johnson, and Roland D. Cusick. 2022. "Modeling the Plantwide Implications of Struvite Loss from Sidestream Precipitation Reactors." *ACS ES and T Engineering* 2 (5): 874–85. https://doi.org/10.1021/acsestengg.1c00404.

[2] Arnell, Magnus, Magnus Rahmberg, Felipe Oliveira, and Ulf Jeppsson. 2017. "Multi-Objective Performance Assessment of Wastewater Treatment Plants Combining Plant-Wide Process Models and Life Cycle Assessment." *Journal of Water and Climate Change* 8 (4): 715–29. https://doi.org/10.2166/wcc.2017.179.

[3] Cornejo, Pablo K. 2015. "Environmental Sustainability of Wastewater Treatment Plants with Resour Ated with Resource Reco Ce Recovery: The Impact of Context and y: The Impact of Context And." https://digitalcommons.usf.edu/etd.

[4] Diaz-Elsayed, Nancy, Nader Rezaei, Tianjiao Guo, Shima Mohebbi, and Qiong Zhang. 2019. "Wastewater-Based Resource Recovery Technologies across Scale: A Review." *Resources, Conservation and Recycling*. Elsevier B.V. https://doi.org/10.1016/j.resconrec.2018.12.035.

[5] Drechsel, Pay, Olfa Mahjoub, and Bernard Keraita. 2015. "Social and Cultural Dimensions in Wastewater Use." In *Wastewater*, 75–92. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-017-9545-6_5.

[6] Duan, Menglin, Edward O'Dwyer, David C. Stuckey, and Miao Guo. 2019. "Wastewater To Resource: Design of a Sustainable Phosphorus Recovery System." *ChemistryOpen* 8 (8): 1109–20. https://doi.org/10.1002/open.201900189.

[7] Dynamita. 2020. "Sumo Manual."

[8] Envirosim. n.d. "BioWin Help Manual."

[9] FAO. 2022. *The State of the World's Land and Water Resources for Food and Agriculture 2021 – Systems at Breaking Point*. *The State of the World's Land and Water Resources for Food and Agriculture 2021 – Systems at Breaking Point*. FAO. https://doi.org/10.4060/cb9910en.

[10] Faris, Ahmed M., Haider M. Zwain, Majid Hosseinzadeh, and Seyed Mostafa Siadatmousavi. 2022. "Modeling of Novel Processes for Eliminating Sidestreams Impacts on Full-Scale Sewage Treatment Plant Using GPS-X7." *Scientific Reports* 12 (1). https://doi.org/10.1038/s41598-022-07071-0.

[11] Fernández-Arévalo, T., I. Lizarralde, F. Fdz-Polanco, S.I. Pérez-Elvira, J.M. Garrido, S. Puig, M. Poch, P. Grau, and E. Ayesa. 2017. "Quantitative Assessment of Energy and Resource Recovery in Wastewater Treatment Plants Based on Plant-Wide Simulations." *Water Research* 118 (July): 272–88. https://doi.org/10.1016/j.watres.2017.04.001.

[12] Fernández-Arévalo, T., I. Lizarralde, M. Maiza, S. Beltrán, P. Grau, and E. Ayesa. 2017. "Diagnosis and Optimization of WWTPs Using the PWM Library: Full-Scale Experiences." *Water Science and Technology* 75 (3): 518–29. https://doi.org/10.2166/wst.2016.482.

[13] Fishwick, Paul. 1995. "Simulation Model Design." *Procedeings of the 1994 Winter Simulation Conference*.

[14] Flores-Alsina, Xavier, Elham Ramin, David Ikumi, Theo Harding, Damien Batstone, Chris Brouckaert, Sven Sotemann, and Krist V. Gernaey. 2021. "Assessment of Sludge Management Strategies in Wastewater Treatment Systems Using a Plant-Wide Approach." *Water Research* 190 (February). https://doi.org/10.1016/j.watres.2020.116714.

[15] Hanhoun, Mary, Ludovic Montastruc, Catherine Azzaro-Pantel, Béatrice Biscans, Michèle Frèche, and Luc Pibouleau. 2011. "Temperature Impact Assessment on Struvite Solubility Product: A Thermodynamic Modeling Approach." *Chemical Engineering Journal* 167 (1): 50–58. https://doi.org/10.1016/j.cej.2010.12.001.

[16] House, The White. 2012. "National Bioeconomy Blueprint, April 2012." *Industrial Biotechnology* 8 (3): 97–102. https://doi.org/10.1089/ind.2012.1524.

[17] Hydromantis. 2018. "GPS-X Lite Exercises."

[18] Jlia, Guangan, Hu Zhang, Joerg Krampe, Tim Muster, Baoyu Gao, Nanwen Zhu, and Bo Jin. 2017. "Applying a Chemical Equilibrium Model for Optimizing Struvite Precipitation for Ammonium Recovery from Anaerobic Digester Effluent." *Journal of Cleaner Production* 147 (March): 297–305. https://doi.org/10.1016/j.jclepro.2017.01.116.

[19] Kiselev, A.V., and E.R. Magaril. 2019. "Ensuring Water Treatment Assessment Within Spatial Ecological and Economic Security Framework Towards Circular Economy." *Bulletin of Ural Federal University Series Economic and Management* 18: 911–29.

[20] Kroiss, H. 2004. "What Is the Potential for Utilizing the Resources in Sludge?" *Water Science and Technology* 49 (10): 1–10. https://doi.org/10.2166/wst.2004.0595.

[21] Kumar, Vineet, Muhammad Bilal, and Luiz Fernando Romanholo Ferreira. 2022. "Editorial: Recent Trends in Integrated Wastewater Treatment for Sustainable Development." *Frontiers in Microbiology*. Frontiers Media S.A. https://doi.org/10.3389/fmicb.2022.846503.

[22] Leeuwen, Kees van, Eli de Vries, Stef Koop, and Kees Roest. 2018. "The Energy & Raw Materials Factory: Role and Potential Contribution to the Circular Economy of the Netherlands." *Environmental Management* 61 (5): 786–95. https://doi.org/10.1007/s00267-018-0995-8.

[23] Lin, Yanzi, Miao Guo, Nilay Shah, and David C. Stuckey. 2016. "Economic and Environmental Evaluation of Nitrogen Removal and Recovery Methods from Wastewater." *Bioresource Technology* 215 (September): 227–38. https://doi.org/10.1016/j.biortech.2016.03.064.

[24] Loosdrecht, Mark C M van, and Damir Brdjanovic. 2014. "Anticipating the next Century of Wastewater Treatment." *Science* 344 (6191): 1452–53. https://doi.org/10.1126/science.1255183.

[25] Marleni, N N N, K N R Putri, and N A Istiqomah. 2020. "Resource Recovery Potential of Wastewater Treatment Plants in Yogyakarta." *IOP Conference Series: Earth and Environmental Science* 599 (1): 012071. https://doi.org/10.1088/1755-1315/599/1/012071.

[26] Morrissey, Karla G., Leah English, Greg Thoma, and Jennie Popp. 2022. "Prospective Life Cycle Assessment and Cost Analysis of Novel Electrochemical Struvite Recovery in a U.S. Wastewater Treatment Plant." *Sustainability (Switzerland)* 14 (20). https://doi.org/10.3390/su142013657.

[27] Musvoto, E V, M C Wentzel, and G A Ekama. 1999. "Integrated Chemical-Physical Processes Modelling-II. Simulating Aeration Treatment of Anaerobic Digester Supernatants." www.elsevier.com/locate/watres.

[28] Nair, Abhilash M., Finn Aakre Haugen, and Harsha Ratnaweera. 2021. "Economic Model Predictive Control for Optimal Struvite Recovery." *Journal of Environmental Management* 280 (February). https://doi.org/10.1016/j.jenvman.2020.111830.

[29] Natividad Marin, Leynard, Max William Burns, and Phil Schneider. 2023. "A Comparison of Struvite Precipitation Thermodynamics and Kinetics Modelling Techniques." *Water Science and Technology*, March. https://doi.org/10.2166/wst.2023.061.

[30] Papa, Matteo, Paola Foladori, Lorena Guglielmi, and Giorgio Bertanza. 2017. "How Far Are We from Closing the Loop of Sewage Resource Recovery? A Real Picture of Municipal Wastewater Treatment Plants in Italy." *Journal of Environmental Management* 198 (August): 9–15. https://doi.org/10.1016/j.jenvman.2017.04.061.

[31] Peccia, Jordan, and Paul Westerhoff. 2015. "We Should Expect More out of Our Sewage Sludge." *Environmental Science & Technology* 49 (14): 8271–76. https://doi.org/10.1021/acs.est.5b01931.

[32] Perwitasari, D S, Universitas Pembangunan Nasional, Jawa Timur Surabaya, Ap Bayuseno, and S Muryanto. 2018. "Modeling and Optimization of Struvite Crystal Scaling Using Experimental Design Methodology For Maleic Acid."

[33] Petzoldt, Claudia Santiviago, and Iván López Moreda. 2016. "Modelling the Thermodynamic Equilibrium of Struvite Precipitation Using a Hybrid Optimization Technique." In *Proceedings of the 6th IASTED International Conference on Modelling, Simulation and Identification, MSI 2016*, 73–81. Acta Press. https://doi.org/10.2316/P.2016.840-040.

[34] Pikaar, Ilje, Jeremy Guest, Ramon Ganigué, Paul Jensen, Korneel Rabaey, Thomas Seviour, John Trimmer, Olaf van der Kolk, Céline Vaneeckhaute, and Willy Verstraete. n.d. *Resource Recovery from Water Principles and Application*.

[35] Pikaar, lje, Katrin Doedere, Tessa van den Brand, Olaf van der Kolk, and Wolfgang Gernjak. 2022. *Resource Recovery from Water*. *Resource Recovery from Water*. IWA Publishing. https://doi.org/10.2166/9781780409566.

[36] Puchongkawarin, C., C. Gomez-Mont, D. C. Stuckey, and B. Chachuat. 2015. "Optimization-Based Methodology for the Development of Wastewater Facilities for Energy and Nutrient Recovery." *Chemosphere* 140 (December): 150–58. https://doi.org/10.1016/j.chemosphere.2014.08.061.

[37] Puyol, Daniel, Damien J. Batstone, Tim Hülsen, Sergi Astals, Miriam Peces, and Jens O. Krömer. 2017. "Resource Recovery from Wastewater by Biological Technologies: Opportunities, Challenges, and Prospects." *Frontiers in Microbiology* 7 (January). https://doi.org/10.3389/fmicb.2016.02106.

[38] Regmi, Pusker, Heather Stewart, Youri Amerlinck, Magnus Arnell, Pau Juan García, Bruce Johnson, Thomas Maere, et al. 2019. "The Future of WRRF Modelling – Outlook and Challenges." *Water Science and Technology* 79 (1): 3–14. https://doi.org/10.2166/wst.2018.498.

[39] Rodriguez, Diego J, Hector Alexander Serrano, Anna Delgado, Daniel Nolasco, and Gustavo Saltiel. 2020. "From Waste to Resource Shifting Paradigms for Smarter Wastewater Interventions in Latin America and the Caribbean." www.worldbank.org.

[40] Shalaby, M. S., Sh El-Rafie, A. H. Hamzaoui, and A. M'nif. 2015. "Modeling and Optimization of Phosphate Recovery from Industrial Wastewater and Precipitation of Solid Fertilizer Using Experimental Design Methodology." *Chemical and Biochemical Engineering Quarterly* 29 (1): 35–46. https://doi.org/10.15255/CABEQ.2014.2107.

[41] Shaw, Andrew, Dave Koch, Steve Wirtel, Ahren Britton, Yvonne Lefler, Catherine O'connor, and Ting Lu. n.d. "Phosphorus Recovery as a Strategy to Meet Tightening Effluent Standards with Significant Additional Benefits."

[42] Sokolowski, John A, and Catherine M Banks. n.d. "Modeling and Simulation Fundamentals Theoretical Underpinnings and Practical Domains."

[43] Solon, Kimberly, Eveline I. P. Volcke, Mathieu Spérandio, and Mark C. M. van Loosdrecht. 2019. "Resource Recovery and Wastewater Treatment Modelling." *Environmental Science: Water Research & Technology* 5 (4): 631–42. https://doi.org/10.1039/C8EW00765A.

[44] Tchobanoglous, George, Franklin L Burton, and H David Stensel. 2014. "Wastewater Engineering Treatment and Reuse (Fourth Edition)."

[45] Tomei, Maria Concetta, Valentina Stazi, Saba Daneshgar, and Andrea G. Capodaglio. 2020. "Holistic Approach to Phosphorus Recovery from Urban Wastewater: Enhanced Biological Removal Combined with Precipitation." *Sustainability (Switzerland)* 12 (2). https://doi.org/10.3390/su12020575.

[46] Türker, Mustafa, and Ipek Çelen. 2011. "Chemical Equilibrium Model of Struvite Precipitation from Anaerobic Digester Effluents." *Turkish Journal of Engineering and Environmental Sciences* 35 (1): 39–48. https://doi.org/10.3906/muh-1008-15.

[47] UN. 2012. "Managing Water under Uncertainty and Risk Report 4 Volume 1." www.unwater.org/documents.html.

[48] ———. 2016. "The State of Renewable Energies in Europe Edition 2016 16 Th EurObserv'ER Report."

[49] ———. 2017a. "A/RES/71/222 71/222. International Decade for Action, 'Water for Sustainable Development.'"

[50] ———. 2017b. *Wastewater : The Untapped Resource : The United Nations World Water Development Report 2017*.

[51] ———. 2022. "The Sustainable Development Goals Report."

[52] UN Water. 2016. "Water and Sanitation Interlinkages across the 2030 Agenda for Sustainable Development 2."

[53] Varjani, Sunita, Ashok Pandey, and Vivek N. Upasani. 2020. "Oilfield Waste Treatment Using Novel Hydrocarbon Utilizing Bacterial Consortium — A Microcosm Approach." *Science of The Total Environment* 745 (November): 141043. https://doi.org/10.1016/j.scitotenv.2020.141043.

[54] WEF. 2014. "Moving Toward Resource Recovery Faciliti." *Water Environment Federation*.

[55] World Economic Forum. 2022. *The Global Risks Report 2022*. World Economic Forum.

[56] Xie, Xiongfei, Daniel E. Giammar, and Zimeng Wang. 2016. "MINFIT: A Spreadsheet-Based Tool for Parameter Estimation in an Equilibrium Speciation Software Program." *Environmental Science and Technology* 50 (20): 11112–20. https://doi.org/10.1021/acs.est.6b03399.

[57] Yadav, Geetanjali, Arpit Mishra, Parthasarathi Ghosh, Raveendran Sindhu, Vandana Vinayak, and Arivalagan Pugazhendhi. 2021. "Technical, Economic and Environmental Feasibility of Resource Recovery Technologies from Wastewater." *Science of The Total Environment* 796 (November): 149022. https://doi.org/10.1016/j.scitotenv.2021.149022.

[58] Ye, Xin, Dongyuan Chu, Yaoyin Lou, Zhi Long Ye, Ming Kuang Wang, and Shaohua Chen. 2017. "Numerical Simulation of Flow Hydrodynamics of Struvite Pellets in a Liquid–Solid Fluidized Bed." *Journal of Environmental Sciences (China)* 57 (July): 391–401. https://doi.org/10.1016/j.jes.2016.11.019.

[59] Yoshida, Hiroko, Zhongtian Li, Gerhard Forstner, and Rajeev Goel. 2019. "Full Scale Implementation of Airprex Phosphorus Recovery and the Development of a Mechanistic Process Model in GPS-X^{TM}." In *91st Annual Water Environment Federation Technical Exhibition and Conference, WEFTEC 2018*, 5308–16. Water Environment Federation. https://doi.org/10.2175/193864718825138745.