

Addressing Challenge and Upcycle of Biomasses in Wastewater Sludges

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In the context of the management of wastewater purification plants, one of the major critical issues in the last five years has been, and continues to be, the unavailability of sites where the ever-increasing quantities of sludge produced can be disposed of. Within the perspective of minimizing and managing sludge, exploring enhanced solutions like syngas, biochar, and energy production is feasible. However, it is essential to shift the focus upstream and address the issue systematically by intervening appropriately in various sections of wastewater treatment processes. This work addresses the problem of minimizing the sludge produced in purification plants, with an interdisciplinary functional approach. An innovative decision-making digital tool has been developed that integrates the "Data-Driven" Digitalization approach with the "Knowledge Embedded" multidisciplinary one. The results deriving from the use of the software are encouraging because they allow to choose the best operational strategy in order to minimize the quantity of sludge produced by the plant.

1. Introduction

Excessive sludge production is a real challenge faced by wastewater treatment plants on a global scale. In Italy, for example, approximately 3.24 million tonnes of sewage sludge are produced every year. According to studies carried out by Utilitalia, in recent years for each P.E. (inhabitant equivalent) purified, 10 to 25 kg/year of EER 190805 sludge expressed in dry matter are produced. These quantities are expected to increase in the coming years. Managing a civil wastewater purification plant is not at all simple and, often, pursuing the objective of minimizing the quantity of sludge produced leads to neglecting basic aspects of the management of the plant sections (Di Giacomo and Romano, 2022; Jaspal and Malviya, 2020). This problem not only poses logistical difficulties in terms of handling and disposal but also has environmental implications (Bodik and Kubaska, 2013). Consequently, the search for effective solutions revolves around the imperative to alleviate the burden of sludge by actively seeking measures to reduce its production. One main avenue to address the problem of excess sludge involves optimizing biological processes in wastewater treatment. This encompasses the exploration of advanced methodologies, such as modified activated sludge systems or innovative biological reactors. These approaches aim to facilitate the efficient removal of organic matter, minimizing the formation of sludge. Thinking about it carefully, the problem can be addressed directly upstream. It is precisely by introducing wastewater into the sewer system that it is possible, immediately, to reduce the quantity of biomass generated by the biological degradation of the organic substrate. To do this, it is possible to act on the quality of the organic load of the wastewater entering the purifier or in the most representative nodes of the sewerage networks, and gradually, based on the data collected, get further and further upstream. In this way, through this backward procedure, it becomes viable to pinpoint (if any) those industrial production activities guilty of exceeding the allowed discharge limits (IWS, Italian Water Tour, 2022; Festival dell'acqua, 2019). This results in a reduction in the load entering the purification plant with consequent optimization of the purification processes. A wastewater treatment plant

is a complex system designed to treat domestic and industrial wastewater to make it safe for release into the surrounding environment (Vesilind, 2003). Each section of this plant plays a specific role in the purification process, ensuring that wastewater undergoes different treatments to effectively remove pollutants of various nature. Figure 1 shows a typical scheme of a wastewater treatment plant, where the various sections and their function are specified. Initially, in the pre-treatment, a coarse screening is performed to remove larger debris, followed by fine screening to capture smaller particles. Subsequently, sand removal is carried out. The primary treatment is characterized by the sedimentation of suspended solid particles, which settle on the bottom of the sedimentation tank forming the so-called primary sludge. The next phase, secondary treatment, involves biological reactors and several advanced technologies to remove biological pollutants, improving the overall quality of treated water. In the tertiary treatment phase, the focus is on reducing the water content of the sludge through dehydration and removing persistent contaminants, such as heavy metals. Dewatering is essential to reduce sludge volume, facilitating subsequent management and disposition.

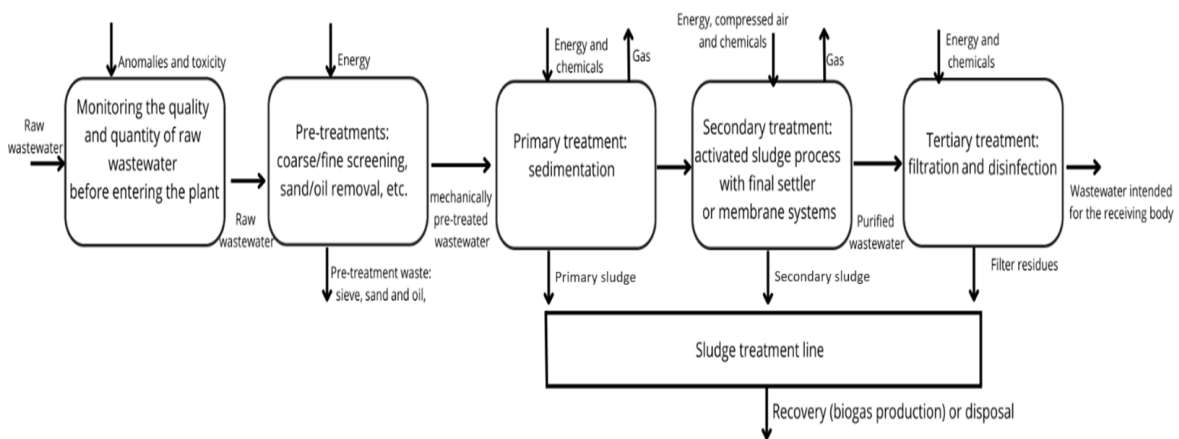


Figure 1. Scheme of a wastewater treatment plant.

Research in the field of urban wastewater treatment is constantly evolving, requiring imperative technological innovation. The need for advancements is crucial to address current environmental challenges and ensure efficient and environmentally friendly wastewater treatment. Morello et al. (2022) presented a detailed and critical assessment of mainstream sludge reduction technologies, exploring their mechanisms across laboratory to full-scale applications. Similarly, Viviani and Corsino (2022) explore diverse methods for minimizing sludge production, such as reducing water line sludge, improving sludge stabilization, or decreasing sludge moisture. Gupta et al. (2022) conducted a comprehensive analysis of wastewater characteristics, conventional treatment approaches, and cutting-edge technologies aimed at eliminating nutrients and heavy metals. More recently Apollo et al. (2023) introduced a modified Activated Sludge (AS) system, known as the Sludge Process Reduction Activated Sludge (SPRAS) process, which achieves significant sludge reduction through *in situ* cell lysis. Cosenza et al. (2024) presented the excess sludge minimization in a Membrane Bioreactor (MBR) system by an Oxidic Settling Anaerobic (OSA) process. As already reported above, sludge treatment represents a crucial element in sustainable wastewater management, requiring advanced strategies for stabilization, biogas production and efficient management of the solid phase. The aerobic approach focused on maximizing stabilization and reducing sludge production (Bengtsson et al., 2019) requires careful control of the often-overlooked SSVs (volatile suspended solids). The anaerobic approach (Nabaterega et al., 2021) instead aims to optimize the stabilization and production of biogas, also requiring the control of SSVs and the evaluation of the yield in terms of quality and quantity of the biogas produced. The application of innovative technologies such as ozonolysis (Otieno et al., 2023) and sludge sonication (Gao et al., 2021) emerges as a promising strategy to reduce sludge production and maximize biogas yield through lysis phenomena. Thermal hydrolysis, both according to classic schemes such as the Cambi (Sahu et al. 2022) process, and through new cold alternatives such as the Orege process technologies (<https://www.orege.com/en/>) presents itself as an option to be evaluated compatibly with energy and environmental balances. In the dehydration process, the use of polyelectrolytes (Cainglet et al., 2020) and the optimization of dosages, based on measurements of the liquid phase and dry residue, are essential. The choice of centrifugal machines (Alt, 2020) is based on a performance comparison, e.g., to obsolete technologies such as belt presses. Filter presses (Nisa, 2019) with filter cloths and polyelectrolyte conditioning offer a more sustainable alternative to traditional chemical methods with lime and ferric chloride (Deneux-Mustine et al., 2001). For the reduction of water content in dehydrated sludge, various technologies are available including traditional thermal drying, drying at low temperatures, bio-drying, and the

use of heat pumps (Pająk, 2013). The adoption of innovative approaches such as drying in solar greenhouses (Gomes et al., 2023) with mechanized or robotic handling of the sludge represents an interesting perspective for improving the overall efficiency of the process. While sewage sludge is classified as a waste, although it consists mainly of biomass, it has great potential and can become a valuable resource through its use in agriculture (as agricultural fertilizer, helping to close the nutrient cycle and reducing dependence on external resources) or in the recovery of energy and materials (Gupta et al., 2022). This practice favors the eco-compatibility of the plant and promotes the responsible use of resources. However, at present there is no universally adopted and definitive solution for the final upcycle of sewage sludge. Many emerging technologies are in the experimental phase. One option is for example the production of synthesis gas for self-generated energy, or the generation of biochar for commercial purposes or for reintegration into the wastewater treatment cycle. Although there are several pilot trials of these processes, large-scale implementation is still lacking. The challenges therefore include large-scale implementation and obtaining the necessary environmental permits.

2. Data Knowledge approach

As part of the new multi-perspective vision of the role played by purification plants in the context of "Climate Change", "Green Revolution and ecological transition" and "Circular Economy and sustainable agriculture" (see PNRR Investments - M2C1 I1.1 <https://www.mase.gov.it/bandi/avviso-m2c1-1-i1-1-linea-b-ammodernamento-e-realizzazione-di-nuovi-impianti-di-trattamento>), this work intends to address the problem of minimizing the sludge produced in purification plants, with an interdisciplinary functional approach. The authors intend to provide an innovative decision-making tool that integrates the "Data-Driven" (DD) Digitalization approach (Cantamessa et al., 2020) with the multidisciplinary "Knowledge Embedded" (KE) one (Shihabudheen and Pillai, 2018). The novel element lies precisely in the use of the "Data Knowledge" combination. This means that on the one hand it is possible to use the data deriving from online measurements as flowrates, levels, temperature, pH, OD, ORP, NH₄, NO₃, NTU, etc. (that is possible today obtain in a sustainable way from the use of modern instrumental technologies for wastewater and sludge). On the other hand, it is possible to use qualitative and quantitative information coming from process experts, i.e. from those who work and know the treatment plants and their characteristics well. (available volumes, microscopic analyzes on activated sludge, presence of foams, anomalous odors, etc.). To date, in fact, the "Data-Driven" (DD) approach (able to make decisions based on objective facts, and not on personal sensations), within the specific reality of purification plants, requires very large and well distributed Multi-parametric Data Bases, often difficultly available or not very reliable for small-to-medium plant sizes. Only some measurement data are relatively simple to acquire, such as those concerning hydraulic measurement (flow rates, volumes, levels, etc.) or electrical consumptions (kW). Others, however, such as those relating to chemical and microbiological parameters (concentrations of nutrient substances, concentrations of MLSS biological sludge, microscopic analysis, SVI Sludge Index, etc.), are obtained through periodic laboratory measurements, or through indirect measurements (see ORP, OD, etc.). Therefore, even in the case of a sustainable DD approach, the frequency of data acquisition (time polling) is standardized per hour, if not per day. The "Knowledge Embedded" (KE) approach allows you to operate with maximum awareness and strategic direction, with the aim of continuously obtaining not only a quality effluent and the simultaneous reduction of the quantity of sludge produced. Through the application of Knowledge Embedded algorithms that use input/output and process parameters, it is possible to determine the Functional Boundary for each treatment section and to define the Residual Treatment Ability. The determination of the input/output data necessary to feed the KE algorithms essentially derives from average daily measurements and hourly measurement data (see inlet flow rate, dissolved oxygen, etc.). On the other hand, however, the KE approach alone, based only on the level of experience and spirit of observation of the process expert, despite being "transversal" and applicable to other systems, has the limit of subjectivity of interpretation. The "Hybrid" KE/DD approach based on the use of the "Data Knowledge" combination (Wrembel and Gamper, 2024) proposed here, operates through knowledge models (Knowledge Modeling) that underlie the functioning of each component of the Water and Sludge Treatment Line supply chain. They start from monitoring the "quality" of the Influent to the plant, using an algorithm that provides a WPR (Water Pollution Rate) index and gradually the algorithms for each treatment section. All with the aim of obtaining possible improvements in terms of compromise between greater reduction in sludge production and corresponding consumption, energy required, reduction of chemical reagents, etc., and always guaranteeing continuous compliance with regulatory discharge limits. The block diagram shown in the Figure 1 can also be interpreted in this perspective of incoming and outgoing data and knowledge. The flows (arrows) of data (Data-Driven) relate to the process parameters, while the knowledge linked to the expertise of expert operators resides within the process rectangles. In wastewater treatment, operating according to the paradigm of environmental sustainability and the circular economy translates into being able to transform a problem (quality of purified water, disposal of waste and sludge produced) into opportunities (recovery and reuse

of water, materials and energy), through the ability to measure the quality of purified water, the energy savings required by the processes, the reduction of waste, the recovery of materials for energy and/or reuse purposes

2.1 Software

The calculation models that use the hybrid “Data Knowledge” approach are the same as those of the SWater-saas Platform, a cloud software ecosystem for modeling and simulation of purification processes.

The SWT (Smart Wastewater Treatments) models of the software platform, while referring to the theoretical-scientific modeling of the State of the Art as IWPRC, ASM1/2/3/, etc. (Metcalf et al., 1991; Filali-Meknassi et al., 2004; Gujer et al, 1999) use an interdisciplinary KE. The software is therefore a tool that allows the user to optimize a purification plant by evaluating the consequences that certain choices of the plant manager can have on the proposed objectives (in qualitative and quantitative terms), considering all those system variables that intervene in the process. In other words, the software, through a combination of data and knowledge that experts have about the system, acts as a decision support with a view to process optimization.

3. Results

Some results generated by the Swater software for small and large sludge purification plants are shown in Figures 2-5. After feeding the required plant data to the SWater-saas Platform, the software allows the user (for example the manager of the plant) to relate some quantities (dependent variables) with operating variables of the system (independent variables) and to evaluate in quantitative terms the advantage that would derive from the use of a certain operational strategy. Some results generated by the software are shown in next figures when varying the “Mixed Liquor Suspended Solids” MLSS [mg/L], i.e., a key parameter used in wastewater treatment to measure the concentration of suspended solids, including bacteria and other microorganisms, in the mixed liquid within a biological reactor. Those who manage sludge purification plants know well that the quantity Q_w [m³/d], excess flow rate (primary and secondary sludge in Figure 1), decreases as MLSS increases, (this means that the amount of purge going to the sludge line decreases, so there is less sludge volume to handle) but no one would be able to quantify this variation in percentage terms, the software can. With the Conventional Activated Sludge (CAS) Process and with an increase from 4.000 to 7.000 of MLSS [mg/L] a reduction up to a maximum of 43% in the purge water flow Q_w [m³/d] is obtained, respectively, in a small-sized 10000 AE (i.e., equivalent inhabitants) plant (Figure 2) and large-sized 100000 AE plant (Figure 3); correspondingly, a reduction occurs in F_w [kg/d] (quantity of solids contained in the excess flow) from 1.7% up to a maximum of 5.3%, in a small-sized (Figure 4) and large-sized system (Figure 5).

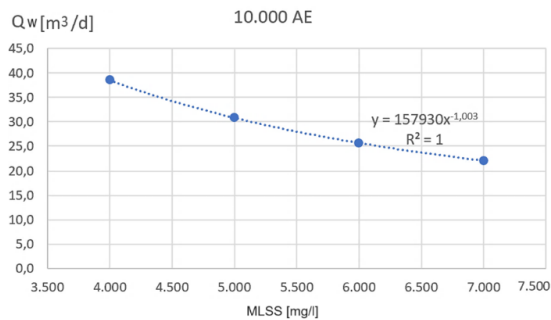


Figure 2. Q_w vs MLSS for 10000 AE plant.

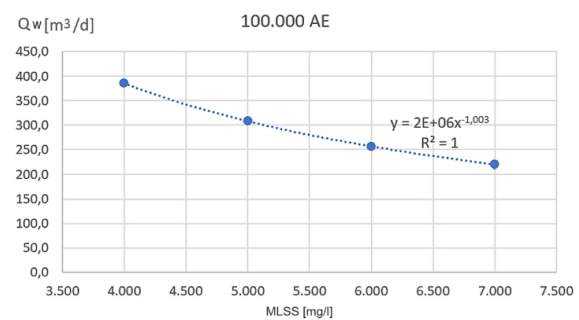


Figure 3. Q_w vs MLSS for 100000 AE plant.

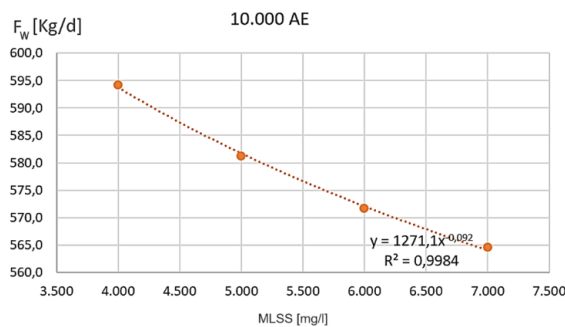


Figure 4. F_w vs MLSS for 10000 AE plant.

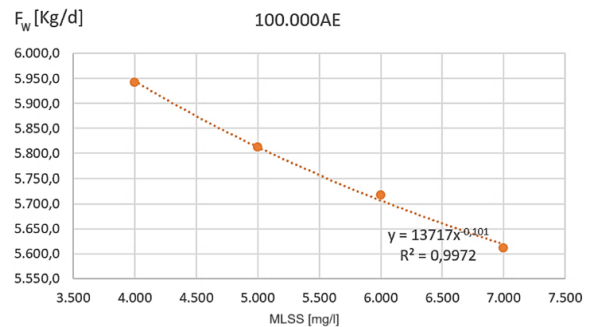


Figure 5. F_w vs MLSS for 100000 AE plant.

The software also provides indications on changes in operational strategies. Figure 6 shows how the quantity of sludge produced varies with the size of the plant, comparing the stabilization of the sludge via aerobic and

anaerobic processes. On average, the reduction occurs when passing from the Anaerobic stabilization process to the Aerobic stabilization one is approximately 8.7% (progressively unfavorable, however, from an energy point of view). The strength of the SWater-saas platform is that it allows the user to study different plant scenarios (with all the parameters that define it) concerning different targets, in this case that of the reduction of sludge produced by the purification plant. Minimizing the quantity of sludge produced is just one of the software's objectives. The others concern the quality of the effluent and the quantity of energy required for the operation of the plant.

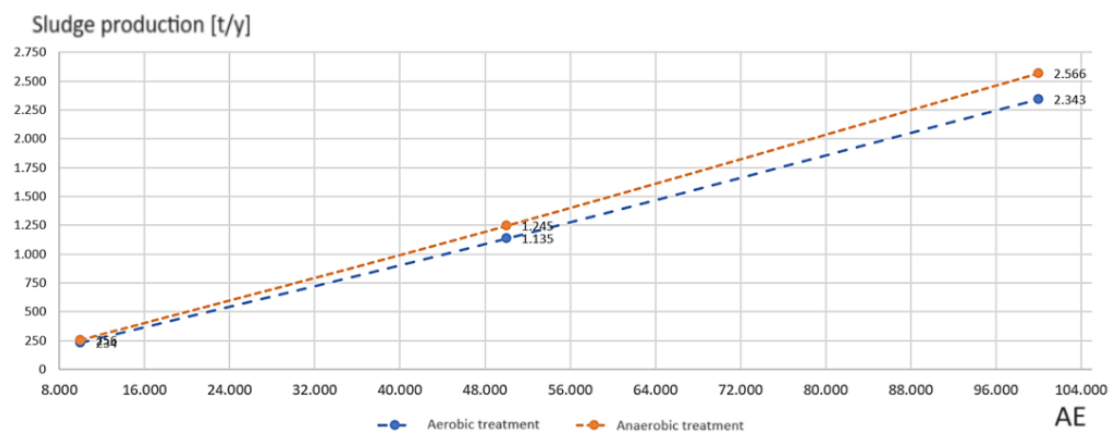


Figure 6. Sludge production vs AE (plant size) for Aerobic treatment and Anaerobic treatment.

4. Conclusions

Sludge wastewater treatment plants are a multidisciplinary and complex field. Their efficient management requires skills ranging from chemistry to biology and from physics to engineering. The SWater-saas platform software presented here, based on the knowledge that experts have of the purification plants and on the data available, is a Data knowledge tool that allows the user (for example the plant manager) to operate in the best possible way, verifying and simulating the operation of the system and at the same time taking into account all the system variables that intervene in the process. To minimize the quantity of sludge produced, the authors obtained useful quantitative/numerical results about one of the possible operational scenarios by feeding sound historical data to the software and by properly tuning its modeling tools. In this way, the plant manager will be able to choose the best solution which translates into tons of sludge not produced and therefore into savings on disposal costs. Optimizing the operational management of wastewater and sludge treatment sections to minimize the annual production of sludge biomass can improve the sludge composition, reducing the risk of microbiological pollution and keeping critical values such as DOC low (not exceeding 100 mg/l). This optimization makes sewage sludge more environmentally friendly, allowing it to be directed towards recovery sites, such as agricultural ones for example. It also sets the stage for future advanced recovery technologies, such as the production of biocrude oil, syngas, and biochar, which could be implemented on a large scale.

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References

- Alt C., 2020, Centrifuges for sludge treatment. In *Water, Wastewater, and Sludge Filtration* (pp. 249-273). CRC Press.
- Apollo S., Seretlo M., Kabuba J., 2023, In-situ sludge degradation and kinetics of a full scale modified activated sludge system achieving near zero sludge production, *Journal of Water Process Engineering*, Volume 53, 103864.
- Bengtsson S., De Blois M., Wilén B. M., Gustavsson D., 2019. A comparison of aerobic granular sludge with conventional and compact biological treatment technologies. *Environmental technology*, 40(21), 2769-2778.
- Bodik I., Kubaska M., 2013, Energy and sustainability of operation of a wastewater treatment plant. *Environment Protection Engineering*, 39(2), 15-24.

- Bordogna G., 2023, Regional knowledge: sources, representation and management. In *Knowledge Management for Regional Policymaking* (pp. 23-43). Cham: Springer International Publishing.
- Cainglet A., Tesfamariam A., Heiderscheidt E., 2020, Organic polyelectrolytes as the sole precipitation agent in municipal wastewater treatment. *Journal of Environmental Management*, 271, 111002.
- Cantamessa M., Montagna F., Altavilla S., Casagrande-Seretti A., 2020, Data-driven design: the new challenges of digitalization on product design and development. *Design Science*, 6, e27.
- Cosenza A., Di Trapani D., Bosco Mofatto P. M., Mannina G., 2024, Sewage sludge minimisation by OSA-MBR: A pilot plant experiment, *Chemosphere*, Volume 347, 140695, ISSN 0045-6535.
- Deneux-Mustin S., Lartiges B. S., Villemin G., Thomas, F., Yvon, J., Bersillon, J. L., & Snidaro, D. (2001). Ferric chloride and lime conditioning of activated sludges: an electron microscopic study on resin-embedded samples. *Water Research*, 35(12), 3018-3024.
- Di Giacomo, G., Romano, P., 2022, Evolution and Prospects in Managing Sewage Sludge Resulting from Municipal Wastewater Purification. *Energies*, 15 (15), 5633.
- Festival dell'acqua, 2019, Gruppo Hera, Rilevazione scarichi inquinanti nella rete fognaria e allerta automatica con la tecnologia Kando, <https://www.slideshare.net/serviziarete/predizione-eventi-inquinanti-in-rete-fognaria-con-tecnologia-kando-i-casi-mm-e-gruppo-cap-254572267>
- IWS, Italian Water Tour 2022, <https://www.slideshare.net/serviziarete/predizione-eventi-inquinanti-in-rete-fognaria-con-tecnologia-kando-i-casi-mm-e-gruppo-cap-254572267>
- Jaspal D., Malviya A., 2020. Composites for wastewater purification: A review. *Chemosphere*, 246, 125788.
- Metcalf L., Eddy H.P, Tchobanoglous G., 1991, *Wastewater engineering: treatment, disposal, and reuse* (Vol. 4). New York: McGraw-Hill.
- Morello R., Di Capua F, Esposito G., Pirozzi F., Fratino U., Spasiano D., 2022, Sludge minimization in mainstream wastewater treatment: Mechanisms, strategies, technologies, and current development, *Journal of Environmental Management*, Volume 319, 115756.
- Nabaterega R., Kumar V., Khoei S., Eskicioglu, C., 2021, A review on two-stage anaerobic digestion options for optimizing municipal wastewater sludge treatment process. *Journal of Environmental Chemical Engineering*, 9(4), 105502.
- Nisa Q. A. Y. K., 2019, Effect of Pressure Differences on Sludge Filtration Process Efficiency by Using Plate Filter Press. *Journal of Vocational Studies on Applied Research*, 1(2), 22-26.
- Filali-Meknassi Y., Auriol M., Tyagi R. D., Surampalli R. Y., 2004, Treatment of slaughterhouse wastewater in a sequencing batch reactor: simulation vs experimental studies. *Environmental technology*, 25(1), 23-38.
- Gao J., Liu Y., Yan Y., Wan J., Liu F., 2021, Promotion of sludge process reduction using low-intensity ultrasonic treatment. *Journal of Cleaner Production*, 325, 129289.
- Gomes L. A., Gonçalves R. F., Martins M. F., Sogari C. N., 2023, Assessing the suitability of solar dryers applied to wastewater plants: a review. *Journal of Environmental Management*, 326, 116640.
- Gujer W., Henze M., Mino T., Van Loosdrecht M., 1999, Activated sludge model No. 3. *Water science and technology*, 39(1), 183-193.
- Gupta M., Savla N., Pandit C., Pandit S., Gupta P. K., Pant M., Khilari S., Kumar Y., Agarwal D., Nair R.R., Thomas D., Thakur V. K., 2022, Use of biomass-derived biochar in wastewater treatment and power production: A promising solution for a sustainable environment. *Science of the Total Environment*, 825, 153892.
- Otieno B., Khune M., Kabuba J., Osifo P., 2023, Process configuration of combined ozonolysis and anaerobic digestion for wastewater treatment. *Physical Sciences Reviews*, (0).
- Pajač, T. A. D. E. U. S. Z., 2013. Thermal treatment as sustainable sewage sludge management. *Environment Protection Engineering*, 39(2), 41-53.
- Sahu A. K., Mitra I., Kleiven H., Holte H. R., Svensson K., 2022, Cambi Thermal Hydrolysis Process (CambiTHP) for sewage sludge treatment. In *Clean Energy and Resource Recovery* (pp. 405-422). Elsevier.
- Shihabudheen K. V., Pillai G. N., 2018, Recent advances in neuro-fuzzy system: A survey. *Knowledge-Based Systems*, 152, 136-162.
- Vesilind P. (Ed.), 2003, *Wastewater treatment plant design* (Vol. 2). IWA publishing.
- Viviani G., Corsino S. F., 2022, The management of sewage sludge: technologies, critical issue and perspectives. In Giuseppe Frega, Francesco Macchione (a cura di), *Technologies for integrated river basin management*. EdiBios.
- Wrembel R., Gamper J., 2024, Data Analytics and Knowledge Discovery on Big Data: Algorithms, Architectures, and Applications, *Data & Knowledge Engineering*, 102279, ISSN 0169-023X.
- Raissi K., 1994, Total site integration, PhD Thesis, University of Manchester Institute of Science and Technology, Manchester, UK.
- US DoE, 2016, Steam Turbines, US Department of Energy <energy.gov/sites/prod/files/2016/09/f33/CHP-Steam%20Turbine.pdf> accessed 24.07.2017.