Romanian Journal of Civil Engineering, Volume 15 (2024), Number 3

Strategies for Achieving a Net-Zero Carbon Footprint in Wastewater Systems

Strategii pentru atingerea unei amprente de carbon net-zero în sistemele de canalizare și epurarea apelor uzate

Cristina Iacob[1], Anagabriela Deac [1], Dan Mureșan[1], Andrei Bolboacă[1], Teodor Chira[1]

[1] Technical University of Cluj-Napoca
St. Memorandumului 28, Cluj-Napoca, Romania
E-mail: cristina.iacob@insta.utcluj.ro, anagabriela.deac@insta.utcluj.ro, muresan.dan@insta.utcluj.ro, andrei.bolboaca@insta.utcluj.ro, teodor.chira@insta.utcluj.ro

DOI: 10.37789/rjce.2024.15.3.16

Abstract. *The world is currently undergoing a transition from a linear economy to a circular one, with the wastewater sector offering numerous opportunities for decarbonization and mitigating the impacts of climate change. Urban wastewater systems are significant sources of greenhouse gas emissions, highlighting the need for a shift towards net-zero carbon states. This paper aims to provide insights into minimizing carbon footprints and achieving net-zero carbon conditions in wastewater systems by examining sources of GHG emissions and exploring effective mitigation strategies. Strategies for decarbonization include operational optimization, energy and resource recovery, source separation systems, and decentralization. Implementing these strategies is crucial for reducing the impacts of climate change and achieving sustainability goals in wastewater systems.*

Key words: wastewater systems, wastewater treatment, GHG emissions, mitigation, strategies, carbon footprint, climate change

1. Introduction

Currently, the world is undergoing a transition from a linear economy to a circular one. In the wastewater sector, numerous opportunities and strategies exist for decarbonization and mitigating the impact of climate change. Human activities have driven approximately 1.0°C of global warming above pre-industrial levels. If current trends persist, global warming is expected to reach 1.5°C between 2030 and 2052 [1]. Warming from anthropogenic emissions will persist in the long term, causing climate changes such as sea level rise, extreme weather, ecological imbalance, economic and political insecurities. These risks are influenced by various factors including the magnitude and rate of warming, geographic location, levels of development and vulnerability, and the choices made regarding adaptation and mitigation strategies.

Greenhouse gases (GHGs) contribute to global warming by absorbing energy and limiting the escape of this energy into space. They act like a blanket, insulating the Earth and retaining heat within the atmosphere [2]. Urban wastewater systems, which include sewer networks, wastewater treatment facilities and receiving water bodies, are sources of GHG emissions that contribute to climate change. Removing organic contaminants and nutrients has been the traditional focus of biological wastewater treatment, but nowadays there is a shift toward integrated operations that prioritize resource recovery and reaching a net-zero carbon state.

Wastewater holds significant energy and resource potential, with biogas and nutrient recovery opportunities. Efforts to integrate water, energy, sanitation, and carbon management are crucial, especially in the face of climate change. In wastewater systems, net-zero transitions requirements include energy balance, greenhouse gas emissions, chemical use, and sludge disposal. Reducing chemical and transportation impacts, streamlining processes, and optimizing energy use are all necessary to achieve net-zero carbon emissions.

2. GHG emissions in the wastewater systems

According to international protocols and standards [3], GHG emissions can be categorized in:

- Scope 1 emissions, which are direct GHG emissions arising from sources controlled or managed by the reporting entity.
- Scope 2 emissions, which are indirect GHG emissions associated with production of energy that has been purchased by the reporting entity (e.g. electricity, steam, heat, or cooling).
- Scope 3 emissions represent all other indirect emissions, which may involve emissions linked with material production, including extraction of raw materials and the production processes of purchased materials, fuels, or services.

Figure 1 illustrates the classification presented above.

The greenhouse gas emissions linked to the water supply and wastewater cycle must take into consideration all emissions occurring throughout the process. This includes water withdrawal, treatment, and transportation, as well as consumer use, disposal, emissions from sewer networks, wastewater treatment, and final discharge. The waste industry, which includes wastewater systems and landfills, is responsible for around 3% of all anthropogenic greenhouse gas emissions worldwide [5].

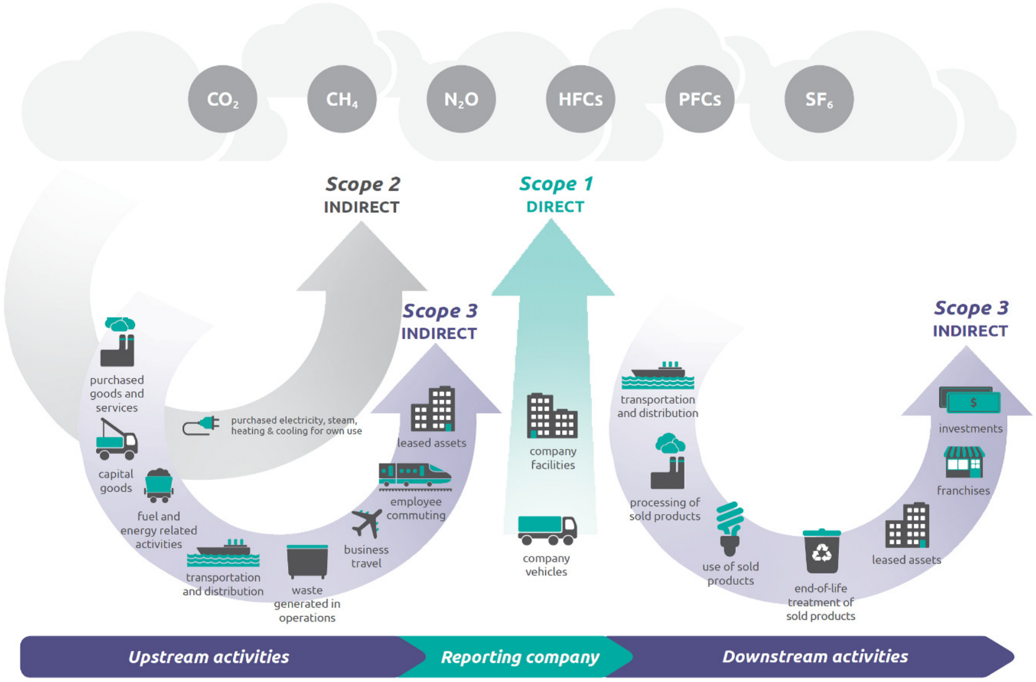

Fig. 1. Overview of GHG Protocol scopes and emissions [4]

2.1. Scope 1

Scope 1 emissions in the wastewater sector include both wastewater collection and treatment. The collection segment involves direct gas emissions - CH4, N2O, and H2S, that are released in sewers in the absence of oxygen.

The emission of gases originates from biological processes happening inside sewer pipes, prompted by the presence of organic matter, nutrients, and microorganisms. These processes occur in anaerobic, anoxic, or aerobic environments and emanate from sewer sediments (which might accumulate at the base of sewer pipes due to variations in flow), from the water volume, and from biofilms forming on pipe walls.

Scope 1 emissions from the wastewater treatment plants (WWTPs) involve the production of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) arising from the biological wastewater treatment process. These GHG emissions should be controlled and reduced due to their high global warming potential [6].

The Global Warming Potential (GWP) is used to facilitate comparisons of the global warming impacts of various gases. Essentially, it measures how much energy the emissions of one ton of a gas will absorb over a specified period, typically 100 years, relative to the emissions of one ton of carbon dioxide (CO_2). A higher GWP indicates that a given gas has a greater warming effect on Earth compared to CO_2 over that time frame [2]. A carbon dioxide equivalent or CO_2 equivalent, abbreviated as CO_2-eq is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential [7].

CO_2 emissions arise from both the biological treatment process and on-site electricity consumption. In the biological treatment process, organic carbon from wastewater is either incorporated into biomass or oxidized to CO_2.

Promoting energy efficiency in the operation of treatment facilities will help decrease CO_2 emissions from the site, leading to a reduction in treatment costs by boosting energy savings. This approach not only enhances cost-effectiveness but also minimizes the environmental footprint of operational activities.

Nitrous oxide (N_2O) and methane (CH_4) are both potent GHG gases. When emitted to the atmosphere, they significantly contribute to climate change. According to Eurostat, the GWP for methane is 25 and for nitrous oxide 298 [7].

These emissions are sometimes omitted from carbon footprint assessments in the wastewater sector, emphasizing the necessity for a more thorough consideration to truly attain zero emissions.

Globally, wastewater treatment is the fourth largest sector responsible for N_2O emissions and accounts for around 3–10% of all atmospheric N_2O emissions [8].

The nitrification and denitrification processes employed for removing nitrogenous compounds from wastewater lead to the emission of N_2O. The primary source of these emissions is the activated sludge process, where nitrifying bacteria produce N_2O under aerobic or anoxic conditions. While N_2O production in aerobic conditions is solely attributed to ammonia-oxidizing bacteria, both nitrite-oxidizing and ammonia-oxidizing bacteria contribute to its generation under anoxic conditions. Additionally, a small amount of N_2O is produced by the grit and sludge storage tanks onsite.

The primary sources of CH_4 emissions in wastewater treatment facilities are the anaerobic digestion process and its component units, such as the centrifuge, buffer tank for digested sludge, storage tank for dewatered sludge, and exhaust gas from the cogeneration plant.

The sludge processing units contribute to 72% of methane emissions from the wastewater treatment plant, and approximately 1% of the COD (chemical oxygen demand) entering the plant is emitted as methane [5].

Globally, the wastewater sector contributes to roughly 5–7% of anthropogenic CH4 emissions, ranking fifth among major sources, following livestock (32%), oil and gas (25%), landfills (13%), and coal mining (11%) [8].

2.2. Scope 2 – GHGs from energy use

Energy is the main operating cost of wastewater treatment. The North American WWTPs consume approximately 1–4% of the total energy production, and in Europe, the consumption is approximately 1% [9].

Electricity is needed throughout the wastewater system for different operations, which include sewage collection and wastewater treatment and sometimes water reuse. WWTPs are often designed to operate using gravity flow whenever possible, thus ensuring enhanced process security. The wastewater is collected from consumers through the sewer network. Depending on the local ground profile and the position of the wastewater treatment plant, pumping might be necessary for the water to reach the treatment facility. Here, the water quality is corrected in accordance with the prevailing regulations. The treated wastewater is then discharged into a local receiving water body, usually by gravitation. Hence, energy use in wastewater systems is determined by the treated flow, pollutant load, final effluent quality, the types of treatment process employed, level of monitoring and automation and experience of the operations staff.

The processes that consume the greatest amount of energy in the wastewater treatment plant are:

- biological treatment, conventional or advanced, especially aeration and sludge recirculation.
- the sludge line, where conventional or advanced anaerobic digestion is implied, sludge pumping, sludge drying and dewatering.

Scope 2 GHG emissions also include energy generation in the wastewater treatment plant. Biomethane, sometimes called *green gas,* is an effective and environmentally beneficial substitute for natural gas. Biomethane is an enhanced form of biogas, obtained by the removal of water vapor, hydrogen sulfide, and carbon dioxide. Because it offers the possibility to manage organic waste, provide clean energy, and find novel applications in both urban and rural locations, biomethane is increasingly being used as a carbon-neutral fuel. Nowadays, a lot of large capacity WWTPs collect biogas resulting from the anaerobic digestion of sludges. After that, the biogas can be gathered and utilized to run a combined heat and power (CHP) plant, which can produce steam or hot water as well as electricity that can be used internally at the facility or exported to the power grid.

Even though more complex processes are needed, that demand more energy to run, the extra energy that is created as heat and power from the extra biogas produced, results in a net reduction in greenhouse gas emissions.

2.3. Scope 3 – GHGs from energy use

Scope 3 emissions arise from activities both upstream and downstream of the wastewater system value chain. The categories typically encompassed by scope 3 emissions include:

- purchased goods and services;
- activities related to fuel and energy;
- transportation and distribution, including both upstream and downstream processes;
- waste treatment;
- employee business travel and commuting;
- lease or hire of equipment;
- use of sold products;

- end-of-life treatment of sold products;

As the focus now shifts to net zero emissions and complete responsibility, more organizations are examining their entire value chain to determine the operation's total greenhouse gas effect. Water and wastewater organizations could reduce overall GHG emissions by influencing their suppliers and working with vendors who fully account for their GHG emissions.

3. Strategies and opportunities for decarbonization

Collecting, transporting, and especially treating wastewater to meet the quality standards set by environmental regulations constitute the most energy-intensive aspect of the water infrastructure sector. However, it also represents the sector with the greatest potential for decarbonization or achieving carbon neutrality. There are numerous key opportunities for decarbonization through optimization in wastewater systems. A few of these are briefly described below.

3.1. Operational optimization and control strategies

The opportunities for decarbonization within wastewater systems include various levels of operation, from pumping to sludge treatment [5]. These are shortly presented below.

Wastewater Pumping: Pumping operations, from collecting to effluent, represent a significant portion of energy use. Strategies for reducing energy consumption include using variable frequency drives (VFDs) and smaller pumps to adapt to changing flow rates, conducting pump maintenance to optimize performance, implementing pumping controls such as flow management, and utilizing data-driven strategies for economic and energy benefits.

Secondary Treatment: Secondary treatment consumes substantial energy, particularly for aeration and ammonia oxidation. To reduce the carbon footprint, feasible strategies involve exploring alternative carbon capture methods, maintaining aeration systems for peak performance, monitoring dissolved oxygen and nitrogen species in real-time, and controlling emissions like N_2O.

Sludge Treatment: Decarbonization opportunities in sludge treatment focus on generating more biogas for energy recovery through improved operations, minimizing fugitive methane emissions, reducing flaring of unused biogas, and decreasing chemical usage in sludge concentration processes.

At whole facility level operational strategies include optimizing peak flow and load management and considering the use or reduction of chemicals and additives in plant operations.

Overall, decarbonization involves implementing a combination of strategies across various operational levels to achieve significant reductions in energy use and carbon emissions.

3.2. Energy and resource recovery

Various energy extraction technologies can be used to fit existing WWTPs. These include options like anaerobic digesters or membrane reactors, as well as processes for recovering energy from salinity gradients or osmosis, along with the utilization of fuel cells. These adaptations aim to achieve net-zero carbon emissions. Below are some methods for enhancing operation in anaerobic digestion (AD) technologies and optimizing sludge management, along with a renewable hybrid process for recovering energy from highly saline brine and treated wastewater effluents.

In recent decades, **anaerobic digestion** (AD) has been employed in WWTPs to stabilize sludge while generating biogas. This approach aims to attain energy and carbon neutrality in medium and large capacity municipal WWTPs. AD offers multiple advantages, including the use of energy from produced biogas - as heat or electric power, the potential to recover valuable nutrients from the liquid stream in the form of struvite or other fertilizer products, a decrease in the amount of sludge requiring disposal, and an improvement in the quality of biosolids for land application. On the other hand, AD use in municipal wastewater facilities presents a few challenges such as the possibility of process instability and failure, the need for personnel with training to optimize the process, odor problems, and the limited financial returns from biogas or biosolids.

There are several methods to improve anaerobic digestion (AD) systems in municipal wastewater facilities. Some of these methods include:

- sludge pretreatment for enhancing the overall rate of anaerobic energy conversion by increasing the surface area of solid particles, improving biogas production, and reducing volatile solids.
- providing optimal conditions for microbial activity and biogas production by adjusting parameters including temperature, pH, and hydraulic retention time, resulting in higher energy conversion efficiency.
- use of anaerobic co-digestion by adding co-substrates such as food waste, fats, oils, and grease (FOG), or agricultural residues to increase organic loading and improve biogas yield.
- utilizing biogas effectively for obtaining heat or electricity minimizes the need for using fossil fuels, which lowers carbon emissions from the production of energy.
- employment of nutrient recovery technologies like struvite recovery from centrate might reduce the demand for synthetic fertilizers and reduce the carbon emissions associated with their manufacturing.
- installing methane capture systems to prevent the release of methane into the atmosphere; the captured methane also represents a sustainable energy source, which allows an additional reduction of the carbon footprint.
- a better management of digestate, which is the material left over after anaerobic digestion. Reducing methane emissions during storage and application of digestate can also help reduce the overall carbon footprint.

Pretreatment of sludge before anaerobic digestion is needed to enhance the efficiency of energy conversion. There are various existing pretreatment technologies, such as thermal, chemical, mechanical, and electrical methods, that aim to increase the surface area of solid particles, improve biogas production, and reduce volatile solids. Thermal pretreatment processes like CAMBI™ and EXELYS™ have shown promise in improving anaerobic digestion performance, but their widespread adoption faces challenges such as uncertain net benefits and operational issues related to toxicity, odors, and maintenance [5].

Unintended negative effects also need to be carefully evaluated, such as how thermal pretreatment affects dissolved organic nitrogen and if pretreatment techniques are feasible for mixed waste streams.

Further optimization, economic analysis, and mitigation of operational challenges are necessary to promote the widespread implementation of sludge pretreatment technologies in anaerobic digestion processes.

Salinity gradient energy (SGE) recovery processes

The integration of SGE recovery techniques into WWTPs offers an opportunity to reduce the carbon footprint by producing renewable energy from resources that would otherwise be wasted and reducing dependency on fossil fuel-based energy sources.

SGE recovery processes, also known as osmotic power or blue energy, harness the energy created from the difference in salt concentration between two fluids. It is the thermodynamic reverse of using energy to desalinate saline water [5].

The energy generated when the low-concentration stream, treated wastewater, and the pre-treated high-concentration stream are brought into contact in the reverse electrodialysis membrane module is used to self-power the reclamation treatment performed in the treatment facility (see fig.2).

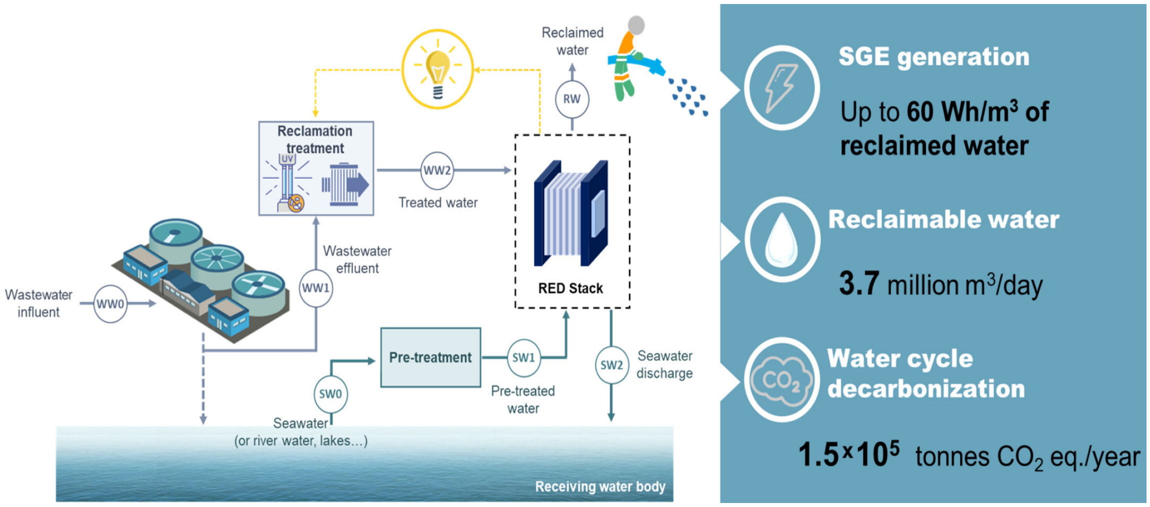

Fig. 2. Salinity gradient energy (SGE) recovery processes flow diagram [10]

3.3. Thermal energy from wastewater

The integration of thermal energy recovery from wastewater with modern district energy systems is a key aspect of sustainable urban heating solutions. Traditional district heating systems, dating back to the 19th century, relied on high-temperature steam or hot water produced through combustion of primary energy sources like coal or natural gas. However, advancements in district heating technology have enabled the utilization of low-grade thermal energy sources, including wastewater, for heating purposes.

These modern district heating systems operate at lower temperatures than their predecessors, allowing for the integration of heat recovery from municipal wastewater. Using heat pumps, thermal energy is extracted from passing sewage and transferred to a secondary hot water loop within the district heating system. This recovered heat is then circulated to end-use systems, contributing to the overall heating needs of connected buildings (see fig.3).

Modern district energy systems may significantly reduce greenhouse gas emissions while offering effective and sustainable heating solutions for urban areas by using wastewater as a thermal energy source.

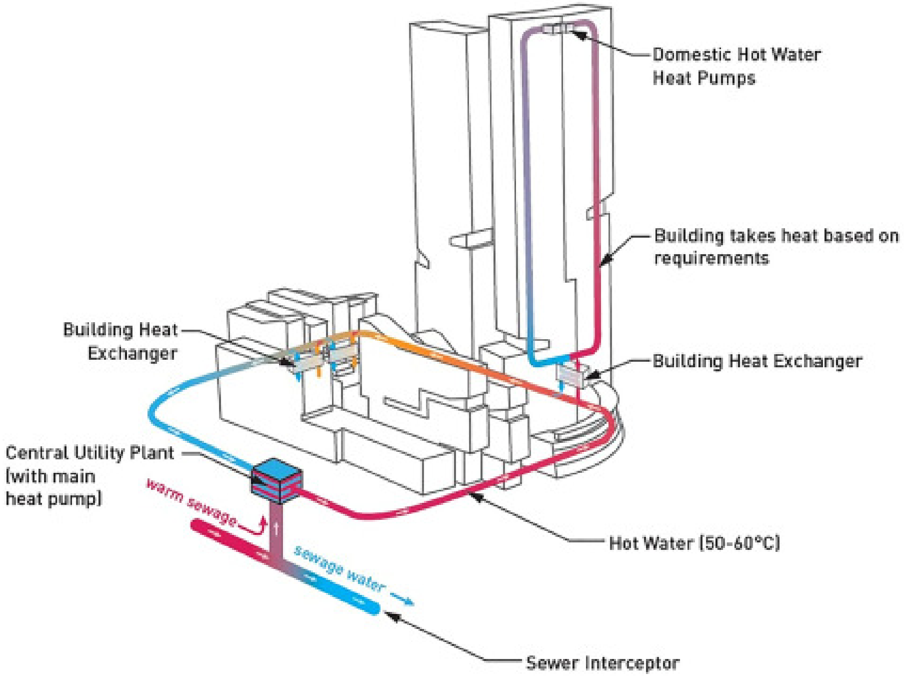

Fig. 3. Schematic of a district heating system sourced to a wastewater interceptor and serving district buildings with building heat and hot water. [5]

3.4. Source separation systems and decentralization.

Source separation systems involve segregating urine and black water (BW) from wastewater, allowing for more efficient nutrient recovery and reducing greenhouse gas (GHG) emissions (see fig.4).

Source separation systems have the potential to enhance the efficiency of wastewater treatment processes, reduce GHG emissions, and improve nutrient recovery, contributing to environmental sustainability.

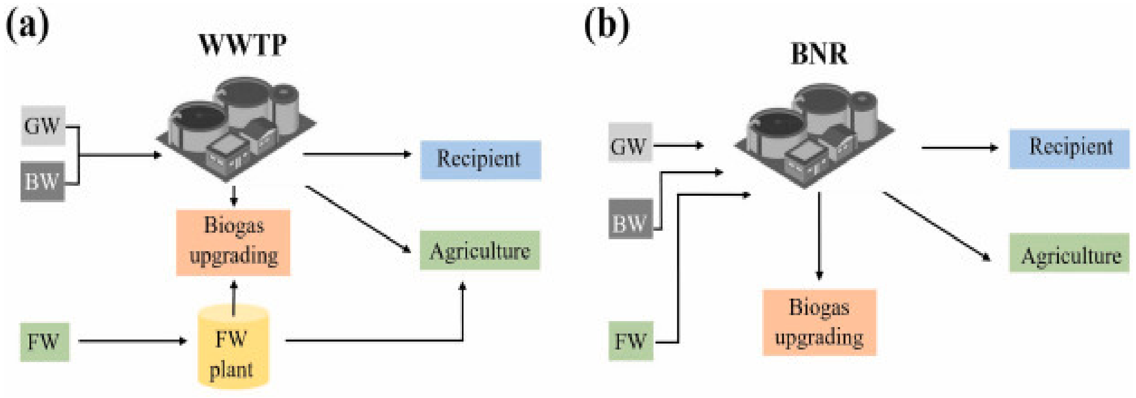

Fig. 4. (a) Conventional systems vs (b) source separation system of wastewater treatment. GW- greywater; BW- blackwater; FW- food waste; BNR- biological nutrient removal [8].

Decentralized wastewater systems have several benefits, including reducing the significant initial investment and operation costs, encouraging the reuse of wastewater, generating employment, and making better use of available space and energy.

These units, which are positioned close to the source of wastewater generation and adapted to specific site conditions, can operate independently or in conjunction with centralized wastewater systems.

Studies suggest that decentralized systems can significantly decrease energy and capital invested in sewage collection and transportation. Natural treatment technologies can be applied, simplifying operations, and reducing costs, particularly beneficial for middle- and lower-income countries. Initiatives like DEWATS aim to implement decentralized treatment and sanitation in developing countries, providing reliable operation and stable effluent quality without technical energy inputs.

4. Conclusions

The transition from a linear to a circular economy presents significant opportunities for decarbonization and mitigating climate change impacts in the wastewater sector.

Understanding and addressing greenhouse gas (GHG) emissions in wastewater systems is essential for reducing climate change and achieving sustainability goals.

By dividing emissions into three categories—Scope 1, Scope 2, and Scope 3—we can identify their sources and develop strategies for reduction.

This paper has explored various aspects of GHG emissions in wastewater systems, including sources, classifications, and impacts, while also presenting mitigation strategies and opportunities for decarbonization.

Strategies towards carbon neutrality include optimizing operations, recovering energy and resources, and integrating cutting-edge technology like thermal energy from wastewater and salinity gradient energy recovery.

By implementing these strategies, wastewater facilities can significantly reduce the carbon footprint of wastewater systems, mitigate climate change impacts, and move towards a more sustainable and resilient future.

References

[1] IPCC – „Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways... „ Cambridge University Press, Cambridge and New York, 2018

[2] https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

[3] https://ghgprotocol.org/

[4] Greenhouse Gas Protocol (WRI, WBSCD) - „Corporate Value Chain (Scope 3) Accounting and Reporting Standard"

[5] Zhiyong Jason Ren, Krishna Pagilla – „Pathways to Water Sector Decarbonization, Carbon Capture and Utilization", IWA Publishing, June 2023

[6] Giorgio Mannina et al. - „Greenhouse gas emissions from integrated urban drainage systems: Where do we stand?", Journal of Hydrology, Volume 559, 2018.

[7]***, Glossary:Carbon dioxide equivalent - Statistics Explained (europa.eu), Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_ equivalent

[8] Mojtaba Maktabifard et al. – „Net-zero carbon condition in wastewater treatment plants: A systematic review of mitigation strategies and challenges", Renewable and Sustainable Energy Reviews, Volume 185, 2023.

[9] Santos, E.,Albuquerque, A., Lisboa, I., Murray, P., Ermis, H. – „Economic Assessment of Energy Consumption in Wastewater Treatment Plants: Applicability of Alternative Nature-Based Technologies in Portugal", Water, Volume 14, 2022.

[10] T. Sampedro, L. Gómez-Coma, I. Ortiz, R. Ibañez - „Unlocking energy potential: Decarbonizing water reclamation plants with salinity gradient energy recovery", Science of The Total Environment, Volume 906, 2024

[11] Rani, A., Snyder, S.W., Kim, H. et al.– "„Pathways to a net-zero-carbon water sector through energy- extracting wastewater technologies", npj Clean Water 5, 49, 2022.

[12] Rissman J., Bataille C., Masanet E., Aden N., Morrow W. R., Zhou N. and Williams E. D. (2020). Technologies and policies to decarbonize global industry: review and assessment of mitigation drivers through 2070. Applied Energy, Volume 266

[13] European Environment Agency - Annual European Union greenhouse gas inventory 1990–2021 and inventory report 2023

[14] Sudeep Nair, Biju George, Hector M. Malano, Meenakshi Arora, Bandara Nawarathna – „Water–energy–greenhouse gas nexus of urban water systems: Review of concepts, state-of-art and methods", Resources, Conservation and Recycling, Volume 89, 2014.

[14] Elena C. Blanco, Mariano Martín, Pastora Vega –"Achieving energy self-sufficiency in wastewater treatment plants by integrating municipal solid waste treatment: A process design study in Spain", Journal of Environmental Chemical Engineering, Volume 11, Issue 5, 2023

[15] M. P. Wilson ,F. Worrall – "The heat recovery potential of 'wastewater': a national analysis of sewage effluent discharge temperatures", Environmental Science: Water Research & Technology, Issue 10, 2021