Politecnico di Torino

Master’s degree in Environmental and Land Engineering
Specialization in Climate Change
A.Y. 2023/2024

Energetic Optimization of Wastewater Treatment Plant and Evaluation of Green House Gases

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ABBREVIATIONS

AD	Anaerobic Digestion
AGS	Aerobic Granular Sludge
AOB	Ammonia-Oxidizing Bacteria
AnAOB	Anammox Bacteria
BOD	Biochemical Oxygen Demand
CANDO	Coupled Aerobic-Anoxic Nitrous Decomposition Operation
CAS	Conventional Activated Sludge
CH_4	Methane
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
COD-OUC	COD Respired by Micro-organisms
DO	Dissolved Oxygen
DAMO	Denitrifying Anaerobic Methane Oxidation
DAMO/A	Denitrifying Anaerobic Methane Oxidation-Anammox
DEFRA	Department for Environment, Food and Rural Affairs
EF	Emission Factor
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
NOSZ	Nitrous Oxide Reductase
N_2O	Nitrous Oxide
N_{dn}	Nitrogen Denitrified
N_{ds}	Nitrogen in Digested Sludge
N_{eff}	Nitrogen Effluent
N_{in}	Nitrogen Influent
N_{rem}	Nitrogen Removal Efficiency
OECD	Organization for Economic Co-operation and Development
$OUNH_4$	Oxygen Uptake Demand for Ammonium
OUDN	Oxygen Uptake Demand for Nitrogen
OUC	Oxygen Uptake Consumption
PD/A	Partial Denitrification-Anammox

PE	Population Equivalent
$P_{influent}$	Phosphorus Influent
$P_{effluent}$	Phosphorus Effluent
$P_{removal}$	Phosphorus Removal Efficiency
PN/A	Partial Nitritation Anammox
PV	Photovoltaic
SCADA	Supervisory Control and Data Acquisition
SNAD	Simultaneous Partial Nitritation Anammox and Denitrification
WWSHP	Wastewater Source Heat Pump
WWTP	Wastewater Treatment Plant

ABSTRACT

Wastewater treatment plants (WWTP) are said to consume significant energy and produce greenhouse gas (GHG) emissions. Enhancing their efficiency is generally important to meet certain targets, especially the use of energy and the reduction of GHG emission at WWTPs as the reduction in GHGs play a major role in promoting sustainability. This current study focuses on analysing the energy usage trends, the main sources of GHG emissions at WWTPs and at the same time suggests effective strategies for their enhancement.

From the existing literature, a review has been conducted to explore the current approaches for decreasing energy consumption and GHG emissions at WWTPs. This literature review encompasses techniques like equipment replacement, retrofitting, process adjustments and incorporating energy sources simultaneously special focus is placed on aeration technologies, high efficiency pumps, biogas upgrading methods and innovative practices such as granular sludge, anaerobic ammonia oxidation and nutrient recovery systems. The strategies found from the review are designed to reduce energy consumption and release of harmful methane (CH_4) and nitrous oxide (N_2O) which are the major contributors to WWTPs GHG emissions.

The baseline scenario outlines the utilization of data from the current literature in order to calculate energy consumption and GHG emissions. Prior to proceeding with the development and comparison of the two optimized scenario the establishment of the baseline scenario is developed. The decision to prioritize enhancing aeration stems from its ability to have an impact, on energy consumption in WWTPs given that aeration typically consumes the most energy. Even a small decrease in aeration energy usage can result in energy savings. On the other hand, the focus of the biogas enhancement plan is to improve the efficiency of biogas production, promote energy recovery and reduce GHG emissions. By comparing these two approaches a comprehensive assessment can be made regarding both energy conservation and recovery potential offering a rounded strategy for optimizing WWTP operations.

The findings indicate that both strategies for improvement lead to reductions in energy consumption and emissions compared to the baseline scenario, with the biogas enhancement plan showing a higher potential for recovering energy. This study offers insights and actionable recommendations, for WWTP operators underscoring the significance of monitoring and adaptive management practices in achieving sustainable wastewater treatment processes.

1. INTRODUCTION

Water is important across various sectors but only a small fraction is suitable for consumption leading to sustainability challenges. Wastewater treatment plants (WWTPs) play a role in safeguarding health by purifying wastewater that contains organic materials, nutrients and chemicals. Failure to treat wastewater can have effects on both the environment and communities, such as oxygen depletion, foul odors and groundwater contamination. Initially designed to remove suspended solids, biological oxygen demand (BOD) and pathogens, modern WWTPs also focus on eliminating nutrients and harmful substances to comply with regulations and preserve water quality.

However, WWTPs use a lot of energy for various stages including mixing, pumping and particularly aeration during the treatment process, typically between 0.5 and 2.0 kWh per cubic meter of treated water with processes for removing nutrients requiring a lot of energy. Besides that, WWTPs also release GHGs including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) which play a role in climate change and their emission amount depends on the technology and processes involved. CO_2 emissions mainly come from treatment processes and electricity use. CH_4 emissions are affected by factors such as the presence of matter, temperature and the type of treatment system in place. N_2O emissions, which have a global warming potential (GWP) considerably more than CO_2, are produced when nitrogen compounds in wastewater break down.

Given the energy usage and GHG emissions linked to WWTPs, there is a growing focus on improving their sustainability and exploring their role in the water energy connection. This study seeks to examine energy consumption patterns, identify sources of GHG emissions in WWTPs and suggest strategies for enhancement. By reviewing existing research, various methods for reducing energy consumption and GHG emissions are explored, including upgrading equipment, retrofitting processes optimizing operations and incorporating energy sources. Special attention is placed on aeration technologies, high efficiency pumps, biogas refinement techniques as well as innovative approaches, like granular sludge utilization, anaerobic ammonia oxidation systems and nutrient recovery methods.

A baseline scenario is set up by using information from existing sources in order to determine the amount of energy used and GHG emissions. And this is followed by creating two improved scenarios. One scenario focuses on making aeration more efficient since it greatly affects energy consumption while the other focuses on enhancing biogas production efficiency, encouraging energy recovery and reducing GHG emissions. By evaluating these strategies, a thorough analysis can be conducted regarding energy conservation and recovery possibilities and reducing GHG emissions.

In summary, this study aims to provide actionable insights and recommendations for WWTP operators, highlighting the importance of monitoring and adjusting management practices to ensure sustainable wastewater treatment processes. The findings emphasize the potential for significant improvements in energy efficiency and reductions in GHG emissions, contributing to the broader goals of environmental sustainability and resource conservation.

1.1. AN OVERVIEW OF WASTEWATER TREATMENT PLANTS AND THEIR SIGNIFICANCE

Water is a resource found in all living beings and plays a crucial role in various aspects such as household activities, industrial processes, irrigation, material transport, energy production and sanitation. Despite covering over 70% of the Earths surface only a small fraction like 0.5 % of water is suitable for use [1]. This limited availability is under pressure due to increasing demands from agriculture, industry and households leading to deteriorating water quality and pollution issues that pose sustainability and public health challenges [2].

The treatment of wastewater is essential to prevent pollution and protect health. Unprocessed wastewater containing substances, nutrients, bacteria and chemicals can reduce oxygen levels in water bodies generate odors and contribute to the eutrophication of aquatic ecosystems, negatively impacting aquatic life and overall water quality. Additionally, the use of wastewater in agriculture can harm groundwater quality and impact farming communities.

Recognizing these critical issues, the evolution of sewage treatment systems originated from the need to address the impact of sewage on the environment and public health. Initially from 1900 until the 1970s the main focus was on eliminating suspended solids, biological oxygen demand (BOD) and disease causing bacteria. Transitioning into the 1970s through the 1990s efforts shifted towards enhancing the ecological aspects of treated wastewater tackling removal and identifying specific harmful substances in sewage. Since the 1990s treatment goals have broadened to include eliminating chemicals and ensuring that treated water meets strict regulatory requirements [22,23].

To sum up, WWTPs play a role in ensuring that clean water is returned to the environment, protecting health and ecological balance. Even though they use a lot of energy, advancements in technology and energy efficient methods can help them promote sustainability while meeting the rising demands, for water and energy.

1.2. ENERGY CONSUMPTION IN WWTP

WWTPs are designed primarily to meet effluent quality standards, often neglecting considerations for energy efficiency which make them highly energy-intensive process especially because of the significant energy demands required for mixing, pumping, and aeration at each stage [24,75]

Their energy consumption depends on their size (population equivalent, organic or hydraulic loading), location of the plant, effluent requirements and characteristics of wastewater. The energy consumption is usually between 0.5 and 2.0 kWh/m^3, with nutrient removal requiring less than 0.5 kWh/m^3. The energy needs for several treatment methods, including lagoons, trickling filters, activated sludge, and advanced treatments, are around 0.09-0.29, 0.18-0.42, 0.33-0.6, and 0.31-0.4 kWh/m^3, respectively [25].

Figure 1 illustrates the average energy consumption of a conventional WWTP with typical unit operations. And it is clear that smaller capacity and more advanced WWTPs generally exhibit higher energy consumption per unit volume [30]. Pratima Singh et al. found that small-scale WWTPs use twelve times as much electricity as larger facilities [18]. Any decentralized treatment facility serving a single community is considered "small-scale" in this study, where it was discovered that the facility's energy consumption was 4.87 kWh/m^3. "Large-scale" was defined as providing centralized conglomerated treatment and servicing big metropolitan areas with an energy consumption of 0.40 kWh/m^3[17].

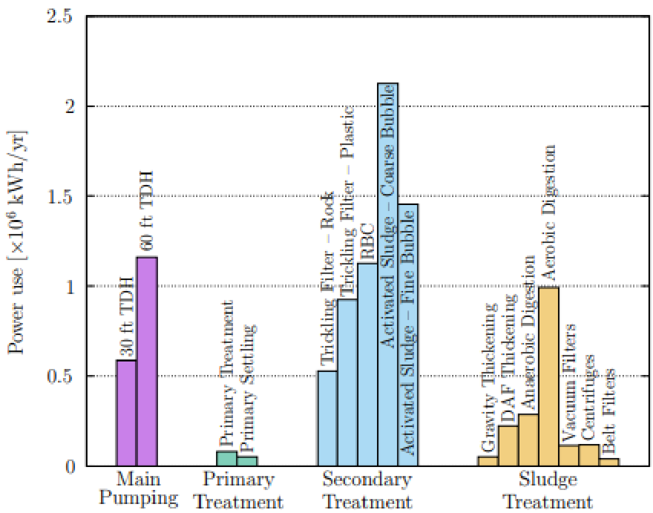

Figure 1: Typical energy use profile for 10 MGD WWTPs [30].

Similarly in another similar study which is a survey characterizing approximately 15000 publicly owned wastewater treatment facilities in the USA reported that unit electricity consumption for different treatment processes vary with the plants size as shown in Figure 2 and it can be seen that with increasing plant size, all four of these processes use less electricity per unit [28].

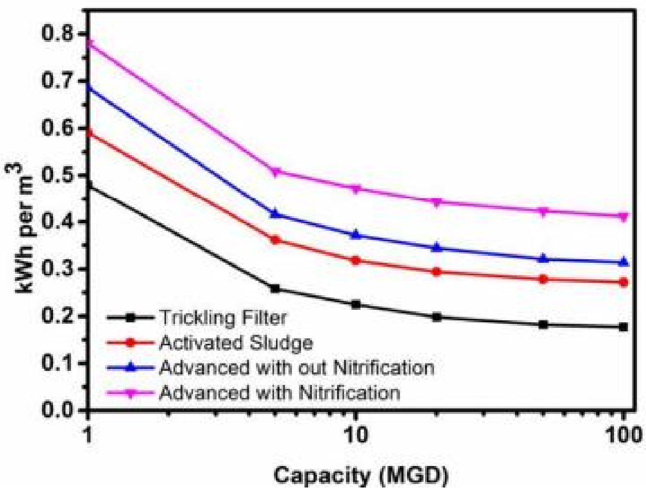

Figure 2: Correlation between WWTP Size and Energy Consumption

More precisely, Figure 3 depicts the energy distribution in a conventional WWTP. It is evident that aeration process in which dissolved oxygen is introduced into the wastewater to support aerobic oxidation uses a substantial amount of energy, accounting for between 50-75% of the overall energy consumption [64]. Anaerobic digestion and wastewater pumping are two other important energy-intensive processes [30].

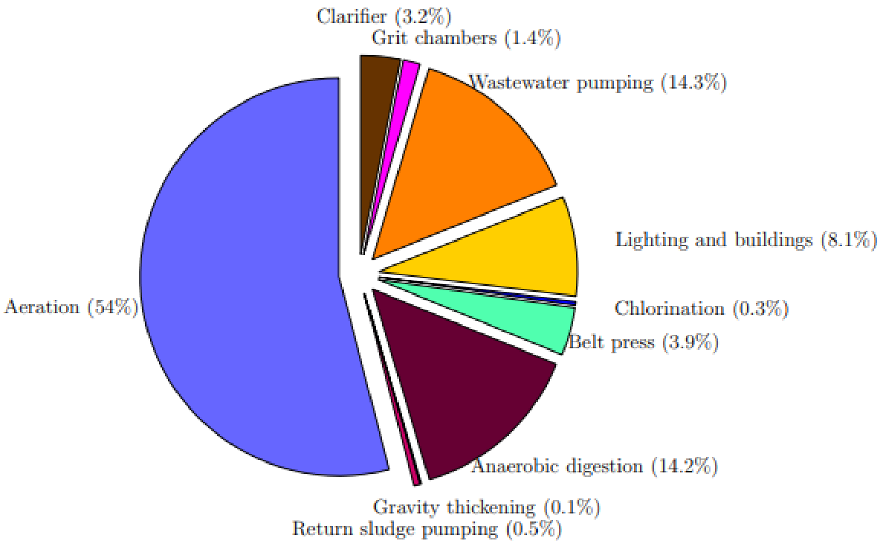

Figure 3: Distribution of energy requirement for conventional WWTPs

The main activities causing energy consumption in wastewater treatment plants can be categorised as follow: Pumping, Treatment (especially aeration), Utilities.

1.2.1. Pumping

Pumping is one of the inevitable part of the entire process where it is used to circulate the water and solids through the sequence of treatment procedures and it requires a lot of energy to convey water from different locations. In locations where gravity flow is essentially impossible, pumping is necessary. Pumps can be utilized at the different places of the facility, including lift stations, influent pump stations, various sites within the treatment plant, and effluent pump stations. And about 15-25% of the energy consumption is caused by them [60].

1.2.2. Treatment

Energy is used extensively in the various wastewater treatment process. Primary treatment, secondary treatment, tertiary treatment and sludge processing are the most often used treatment procedures [59].

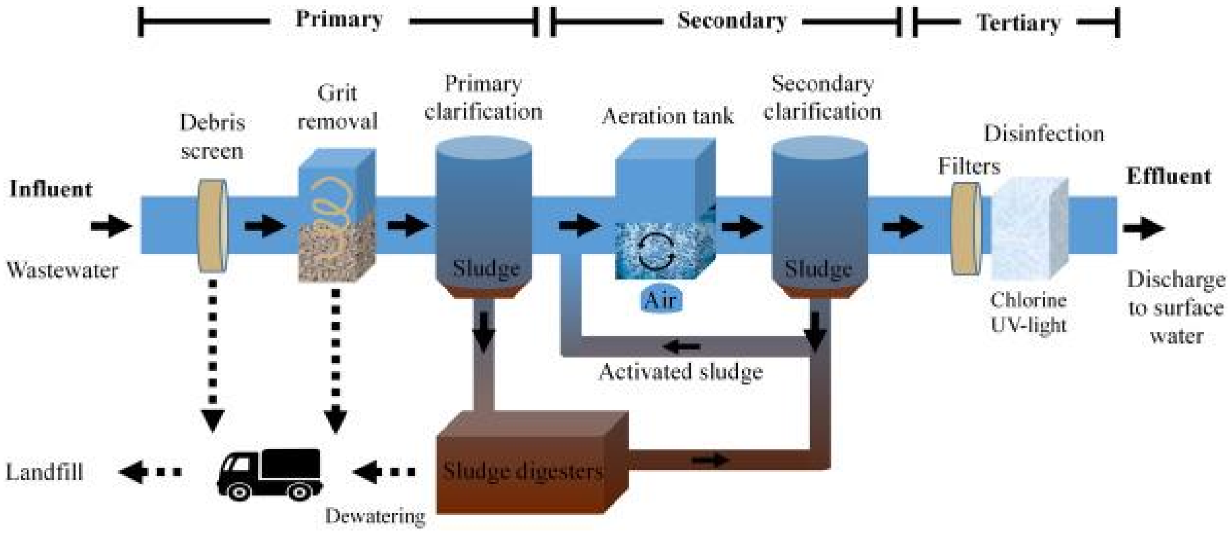

Figure 4: Process flow diagram for wastewater treatment plant [96]

Primary treatment – This step includes operations such as wastewater collection, pumping, screening, grit removal and sedimentation in the primary settling tanks [59].

The treatment starts with screening in order to remove large particles before being ground to smaller the size of the residual solids. After this, the water flows to primary sedimentation tanks where the particles are given time to settle. Particles with higher specific gravity settle at the tank's bottom, while those with lower specific gravity float to the water's surface, and skimmers subsequently remove grease, free oil, and other floating particles from the surface. Commonly, to help remove solids from primary sedimentation tanks, chemical flocculants or polymers are introduced. Solids removed from primary treatment are subsequently dewatered and handled in the sludge treatment procedure [58].

While this treatment step generally demands relatively low energy use, excluding wastewater pumping, it can eliminate approximately 50 to 70% of suspended solids and 25 to 40% of the BOD. Therefore, this process not only operate with efficiency but also play a crucial role in removing contaminants from the wastewater, thereby reducing the load on subsequent processes [30,59].

The efficiency of primary treatment directly affects the amount of energy needed for secondary treatment processes. More specifically, if primary treatment is less effective, more energy will be used, especially for aeration, in order to remove organic matter and nutrients during secondary treatment [30].

Secondary treatment:

Conventional secondary treatment involves biological processes to degrade organic matter and reduce solids. This step is assessed by BOD and suspended solids removal. This process usually takes place in a tank followed by a settling basin or secondary clarifier utilizing techniques such as the activated sludge method and trickling filters.

When nutrient removal, such as nitrogen and phosphorus, is needed, it can be integrated with secondary treatment. Nitrogen removal may require additional reactors for the nitrification-denitrification process, often combining chemical and biological treatments for enhanced efficiency [76].

In the study made by Yang et al. in 2006 at 599 Chinese WWTPs the energy consumption of secondary treatment was measured; the results are shown in the Table 1 [17].

Table 1: Secondary Treatment Energy Input

Secondary Treatment	**kWh/MG Treated**
Activated Sludge	1321
Trickling Filter	954
Extended Aeration	1287
Sequencing Batch	1272
Biomembrane	1249
Oxidation Ditch	1143
Anaerobic-Anoxic-Oxic	1011
Land Treatment	958

The aerobic activated sludge treatment method is accounting for a significant portion of the total energy consumption ranging from 30% to 75% and widely used as a treatment WWTPs. These reactors maintain a suspended bacterial culture known as activated sludge and effectively eliminate dissolved or colloidal material.

During these processes the bacteria break down the organic carbon in the wastewater, resulting in the production of carbon dioxide, nitrogen compounds and biological sludge. This treatment step plays a crucial role, in reducing BOD levels by removing 70% to 85% of BOD from the effluent. The effluent of this step goes to secondary clarifier.

A fraction of the clarifier's sludge is recycled into reactors or aeration basins, while the remainder is removed or "wasted". Several techniques are used to dewater and dispose of the waste sludge. Ultimately, the secondary treatment's effluent is cleaned and released [58].

Since it is going to be discussed in the energy consumption reduction part, it is important to understand technical details about aeration system.

Aeration Methods

There are numerous types of aeration systems, but wastewater is primarily aerated using two basic methods: submerged diffusion, where air or pure oxygen is introduced through diffusers and mechanical surface aeration, which agitates the water to incorporate air [59]. Sub-surface methods encompass coarse-bubble and fine-bubble diffusion, as well as jet aeration. Surface methods involve fixed or floating aerators and various types of paddle aerators. In contemporary, larger WWTPs, sub-surface fine-bubble diffusion aeration is more commonly used [31].

Aeration systems consist of three main components: blowers for generating airflow, airflow transfer and distribution (including pipe,valve,diffusors) and aeration tanks (Figure 5)

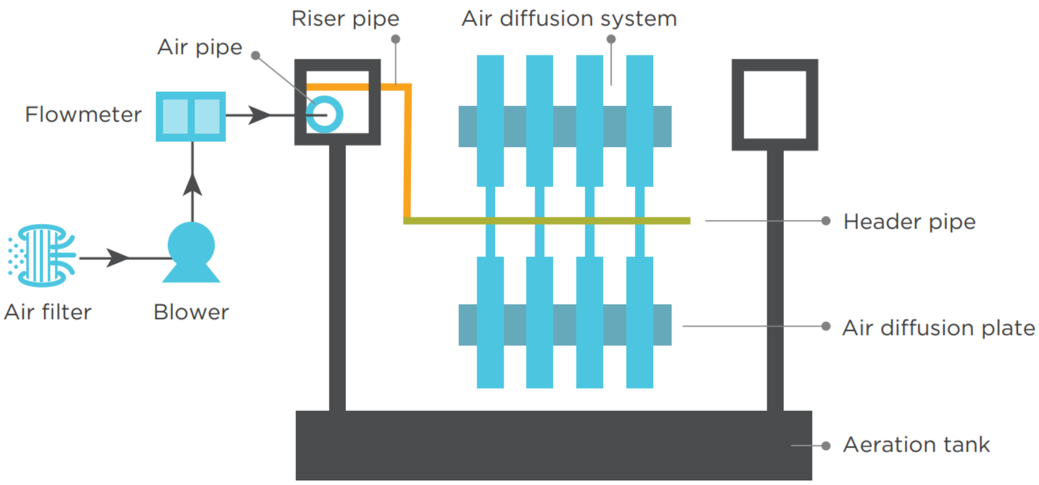

Figure 5: Example of a typical blower and aeration system [31]

Blower

A blower draws in external air, compresses it, and sends it to the distribution pipes, which supply air to the aeration basins in a WWTP. Compression is necessary because the air pressure at the diffusers must exceed the water pressure, particularly since diffusers are typically installed 4-6 m deep, making water pressure a significant factor. Additionally, pressure losses occur in the piping system, and diffusers require a minimum pressure, necessitating even higher blower pressure [50].

Blower technologies are divided into two main categories: centrifugal and positive displacement.

a.Centrifugal: Typically, they offer a broad range of airflow but operate within a narrow pressure range. These blowers are commonly employed in WWTPs that require high airflow, exceeding 425 m^3/min

b. Positive displacement: they can achieve a wide range of pressures but only within a narrow airflow range. Commonly they are employed in WWTP requiring low airflow. The two primary types of positive displacement blowers are rotary lobe and rotary screw.

- **Rotary lobe technology**: This well-established method employs a pair of lobe-shaped rotors, utilizing external compression. Air is compressed outside the casing as it is transferred back from the pressure side.
- **Rotary screw technology**: This newer approach for wastewater applications involves two screws that compress air internally. As the air moves from the inlet to the outlet, the space between the screws narrows, which results in internal compression. This internal compression can potentially make this technology more energy-efficient than rotary lobe technology [50].

Air piping*:* The blower is usually linked to the aeration system via a manifold, allowing for multiple blowers to be connected. The piping system typically uses stainless steel from the blower to the aeration basin, up to one meter above the basin floor.

Valves: Before the pipe system enters the bioreactor, valves control the airflow to each zone. These valves are operated by actuators, and their positions are usually monitored by the Supervisory Control and Data Acquisition system (SCADA). The control system usually sets the valve opening set-point. Butterfly valves are commonly used because of their cost-effectiveness, however they have non-linear characteristics, which makes precise airflow control challenging.

An example is that a 10% valve opening can increase airflow unevenly, depending on the initial valve position.

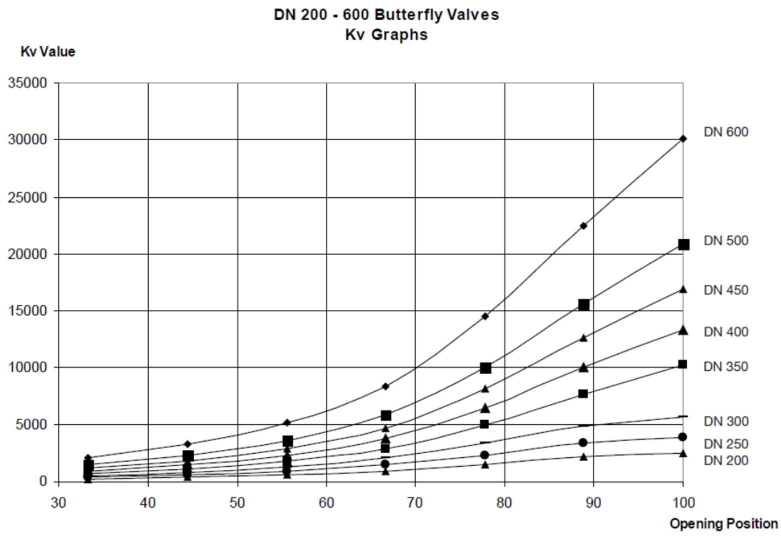

Figure 6: Valve characteristics of butterfly valves.

Plug valve is another type of valve. Even though they are more expensive than butterfly valves, they offer linear characteristics and ensures a consistent increase in airflow regardless of the initial valve position.

Diffusers: Diffusers are connected to the piping system and release air into the wastewater. They are categorized by the size of the bubbles they produce: coarse bubble and fine bubble diffusers.

Coarse bubble diffusers: These diffusers are typically nonporous and have a low oxygen transfer efficiency (OTE). Although they are not energy efficient, they are suitable for applications such as sludge aeration, where fine bubble aeration cannot provide adequate mixing.

Fine bubble diffusers are generally porous and offer higher OTE than coarse bubble diffusers, making them more energy efficient. These diffusers consist of a holder and a membrane with slits through which air passes into the wastewater. The quality and slit design of the membrane affect diffuser pressure loss. Fine bubble diffusers may experience fouling issues as microorganisms tend to adhere to the aeration tools leading to decreased effectiveness. To prevent this problem, regular cleaning is necessary and can be done by air bumping where airflow is increased to stretch the membrane and crack the biofilm or by chemical cleaning where using acid or alkaline washes or gas injection take place.

The increase in oxygen transfer efficiency (OTE) for bubble diffusers is linked to the surface area, which's greater for smaller bubbles because of their extended ascent time and enhanced contact with the wastewater as it can be seen from Table 2. The density of diffusers (diffuser area/tank bottom area) also impacts aeration effectiveness with higher densities proving more efficient but also more expensive [31,50].

Table 2. Area to volume ratio for a typical coarse and fine bubble

Bubble Type	**Typical Diameter (cm)**	**Surface Area (cm^2)**	**Volume (cm^3)**	**Specific Surface Area (cm^2/cm^3)**
Coarse	1	12.6	4.19	30
Fine	0.1	0.126	0.00419	3000

Tertiary treatment

Tertiary treatment is an advanced wastewater treatment process that is not frequently applied to municipal wastewater. However, it has gained significance as the need to comply with discharge requirements set by the EPA and other environmental authorities has grown. As environmental standards become more tighten, tertiary treatment plays a crucial role in achieving the required water quality standards before discharge into the environment or for potential future reuse [58,59,29]

Tertiary treatment eliminates a variety of contaminants that subsequent treatment is unable to eliminate, including organic matter, heavy metals, SS, nutrition, and infections. During this treatment procedure, wastewater effluent is made even cleaner by using stronger and more sophisticated treatment technologies such as disinfection, filtration, advanced oxidation, reverse osmosis, membrane, ultraviolet, electrodialysis, ion exchange, nutrient removal etc. [29,59].

Filtration helps to remove suspended solids while activated carbon is used for toxic compounds

Nutrient removal, especially nitrogen, involves further treatment [58]. Because of the requirements of nutrient removal processes including; nitrification, denitrification biological phosphorous removal, this phase requires substantial energy input. Moreover, energy requirements may increase when it comes to water reclamation or reuse, particularly if advanced treatment technologies like disinfection and reverse osmosis are used [30].

In order to remove BOD from the water to extremely low levels, this stage also involves pumping oxygen into the water, which raises the plant's overall energy usage by 40-50 % [59].

Disinfection:

To inactivate or eliminate pathogenic microorganisms in order to lower the risk of waterborne illness, disinfection processes are used [30]. Chlorination is the most common among them where chlorine gas is introduced to the water to eradicate pathogenic bacteria and lessen odor.

When implemented properly, chlorination can eliminate nearly 99% of dangerous bacteria from effluent streams, demonstrating how much it may improve water quality [59].

Some regions switched from using chlorine to sodium hypochlorite disinfection to reduce the risk of handling, storing and transporting chlorine gas. However, the effluent water produced by chlorine or hypochlorite contains amounts of chlorine that could be hazardous to fish and aquatic life. As a result, excessive chlorine must be eliminated from discharged water by a de-chlorination process, which could increase the need for energy [58]. Due to growing concern over the negative sides of chlorination, ultraviolet radiation has drawn a lot of interest as an alternative disinfection processes [59]. It removes the possible risks and expenses related to handling and storing chlorine gas or other substances containing chlorine. Moreover, it does not leave any chemical residues in the treated water which is a crucial factor for reuse or release of water into a river.

Electromagnetic energy is transmitted to the genetic material of organisms in this system where it prevents the cells from reproducing. A number of variables, including the intensity of UV radiation, duration of exposure and the specific attributes of the wastewater, affect how efficient this UV disinfection method [58].

However, UV consumes more energy than chlorination. In a comparative study of wastewater treatment plants, Owls Head WWTP in New York employing chlorine disinfection, demonstrates substantially lower energy-related carbon footprint (CF) than the Gloversville-Johnstown WWTP in New York, utilizing ultraviolet (UV) disinfection, despite their similar energy mixes. This highlights the advantage of chlorine in terms of energy efficiency [16,82].

Overall, the energy consumption related to different disinfection processes, involves specific components. For chlorine gas disinfection, energy is mostly expended in operating an evaporator heater, pumping dilution water, and pumping chlorine solution. Hypochlorite disinfection requires energy for pumping dilution water and operating metering pumps for hypochlorite. Finally, for ultraviolet disinfection, power is required for UV tube illumination. Understanding these energy inputs is essential to comprehend the overall environmental impact and efficiency of different disinfection methods in wastewater treatment [59].

Sludge Processing:

Sludge processing is a complex process that involves a number of steps, including sludge thickening, stabilizing it with lime or aerobic or anaerobic digestion, sludge dewatering, and finally disposal through landfill, composting, or incineration [58].

These processes may be used differently, based on the particular needs of each plant. Energy plays an essential role in pumping sludge between these operations and sending the finalized sludge to the belt press or sludge discharge truck. Sludge dewatering, which is usually accomplished through continuous belt press operations, focuses on removing water from the sludge while thickening and stabilization work to solidify the sludge. Among all these processes, continuous belt pressing is the primary energy consumer. It's crucial to carry out these steps effectively to lessen the burden on other treatment processes and minimize the impact on landfills [59].

1.2.3. Utilities

The primary energy-consuming utilities in a WWTP include lighting, heating and cooling systems. While these utilities may not individually consume vast amounts of energy, they become significant in facilities with extensive office spaces and laboratories. Implementing energy-efficient systems is recommended to minimize energy consumption [59].

1.3. GHG EMISSIONS FROM WWTP

Together with energy consumption, WWTPs contribute to the emission of GHGs which are playing a role in climate change. The main GHG emissions from WWTPs include CH_4, CO_2 and N_2O. To address these various GHGs uniformly, gases are converted to CO_2 equivalent (CO_2e) based on their capacity to cause global warming over 100 year period .It is clear from the Table 3 that even minimal amounts of N_2O emissions can pose environmental concerns since they have a GWP that is 298 times more than that of CO_2 and therefore N_2O emissions have attracted increased attention [30].

Table 3: The GWP of GHGs produced in WWTPs

Gas	GWP
Carbon dioxide	1
Methane	28
Nitrous oxide	265

1.3.1. WWTPs processes causing to GHG Emissions

GHG emissions from the WWTPs arise from diverse processes within the system and mostly depends on the technology employed.

1.3.1.1.Carbon Dioxide (CO_2):

The two main causes of CO_2 production in the WWTPS are the treatment processes themselves and the electricity consumption associated with these processes. BOD of wastewater undergoes two different routes during the anaerobic phase: it can either be absorbed into biomass or converted into CO_2 and CH_4. Through endogenous respiration, some of the biomass undergoes additional conversion to CO_2 and CH_4. Other sources of CO_2 emissions include combustion of digester gas and sludge digesters. During the aerobic treatment phase part of CO_2 is generated through the decomposition of organic matter occurring in the activated sludge process and, to some extent, in the primary clarifiers [14, 26] CO_2 is excluded from the IPCC Guidelines for WWTP since they are considered biogenic in origin and CO_2 from biogenic sources doesn't contribute to global warming. In the context of the carbon cycle and food chain, "biogenic origin" refers to naturally occurring sources of atmospheric CO_2 that move from plants to animals to humans in a short cycle. In addition to producing CO_2, photosynthesis also takes out a corresponding amount of mass from the atmosphere. This balance endures through subsequent procedures such as respiration or wastewater treatment, maintaining a neutral impact on global warming [26].

1.3.1.2.Methane (CH_4)

CH_4 levels in the atmosphere have been rising steadily over the last ten years, which has been levelled at a notable pace of 9.3 ppb/year according to IPCC report. Wastewater facilities are the fifth-largest source of anthropogenic CH_4 emissions worldwide with the CH_4 emission contribution of 5-7%, after coal mining (11%), oil and gas (25%), livestock (32%), and landfills (13%) [16].

The amount of degradable organic matter in the wastewater, the temperature, and the kind of treatment system employed all have an impact on how much CH_4 is created. Elevated temperatures result in a higher CH_4 production rate, a factor of particular importance in uncontrolled systems and warmer climates [14,26].

On the other hand, when used efficiently, CH_4 can help the facility become energy self-sufficient, which will partially offset CO_2 emissions. In contrast, the plant's CF may worsen if CH_4 leaks or is released due to incomplete combustion. Regional analyses often rely on CH_4 emission factors (EFs), while comprehensive plant-level case studies are less common in existing literature [16].

According to a recent analysis by Song et al. yearly methane emissions from municipal WWTPs in the United States are estimated to be significantly higher than previously predicted by the IPCC. Additionally, Zhao et al. found that methane emissions from Chinese municipal WWTPs were more than three times higher than those from US facilities. Despite some uncertainties in empirical methods, they remain a valuable tool for estimating methane emissions from WWTPs. In order to improve CH_4 emission estimates, Zhang et al. emphasized the significance of carrying out in-depth measurements across a range of treatment procedures, sizes, and locations. A full scale investigation into the long-term CH_4

emissions from the aerobic compartments of a plug-flow was carried out by Ribera-Guardia et al. Peak CH_4 emissions were seen in the initial aerobic zone and decreased towards the bioreactor's end. The researchers hypothesized that methane originated under anaerobic conditions during the initial phases of the plant, later dissipating in the aerobic bioreactor compartment. The plant influent (0.55 mg CH_4 /l) and the reject water from anaerobic digesters (0.52 mg CH_4 /l) had the greatest concentrations of liquid CH_4. In the assessment of CH_4 emission factors of municipal WWTP in South Korea, Hwang et al. observed that the sludge thickening process yielded the highest CH_4 emissions (2.09 g CH_4 /kg BOD), which is significantly more than the aeration basin, primary clarifier and secondary clarifier. In the study where four scenarios of sludge treatment and disposal were examined by Wei et al., incineration contributed the most to CH_4 emissions (45.1%), followed by sanitary landfills (23%), land use (17.7%), and construction materials (14.2%) [16].

Solís et al. employed a modified Anaerobic Digestion Model No. 1 (ADM1) to estimate CH_4 emissions in a plant-wide model. They considered fugitive emissions, accounting for 2.7% of biogas production, which escaped from combined heat and power (CHP) units or leaked from anaerobic digesters. The remaining biogas was assumed to be fully combusted, converting CH_4 to CO2 while generating heat and electricity. Additionally, direct emissions from sludge storage were estimated at 8.7 kg CH_4 per ton of volatile solids (VS). For the studied WWTP with a flow rate of 21,000 m3/d, the total carbon CF was 19,000 kg CO_2e/d, with CH_4 emissions contributing 5.8% to the overall CF [16].

1.3.1.3.Nitrous Oxide (N_2O)

WWTPs contribute significantly to atmospheric N_2O, making up 3-10% of all emissions. As reported in the most recent IPCC assessment, atmospheric N_2O concentrations have been steadily rising over the last years, averaging roughly 0.95 ppb/year and being the fourth-largest source of N_2O emissions, the wastewater treatment industry is highlighted in the report. The process of N_2O release from these facilities is dynamic and frequently out of the plant operators' direct control [16].

N_2O is produced through the degradation of nitrogen components in wastewater, such as urea, nitrate, and protein. In order to remove the nitrogen components from wastewater various techniques ranging from lagooning to advanced tertiary treatments are used in centralized systems [14,26].

1.3.2. Identification of the dominant pathways

N_2O production in WWTPs involves complex microbiological reactions that occur in different environmental conditions. These reactions are facilitated by various microorganisms, including ammonia oxidizing bacteria (AOB) and heterotrophs. AOB-mediated pathways lead to the generation of N_2O as an intermediate during the conversion of ammonia to nitrite, and it can also be produced during autotrophic denitrification. Similarly, heterotrophs contribute to N_2O production as part of the denitrification process. Importantly, if this process proceeds undisturbed, N_2O can be further reduced to dinitrogen (N_2) during the final stages of denitrification, potentially reducing N2O emissions [16].

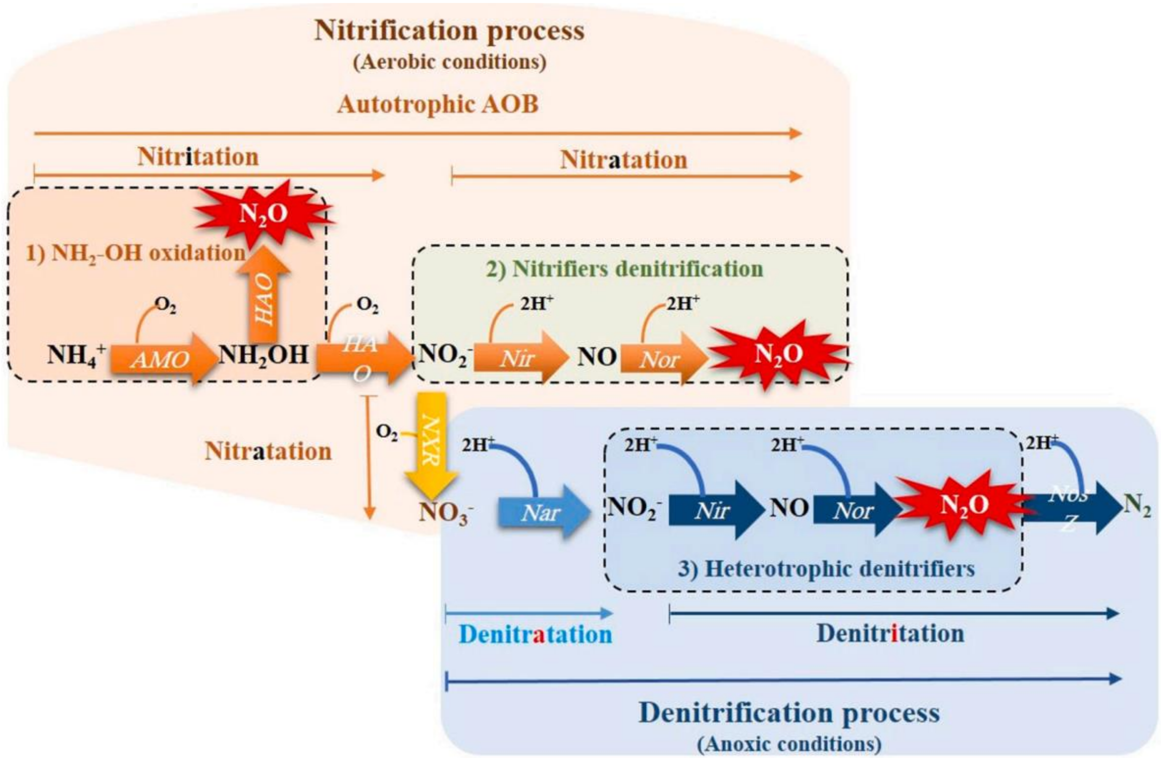

Figure 7: Biological pathways of N2O production and sink in the bioreactors

According to study made by Ni et al. the current emissions of N_2O represent a range of 0.1-25% of the nitrogen consumed during the nitrification and denitrification processes [30].

While nitrification is the aerobic conversion of ammonia into nitrate, denitrification occurs under anaerobic conditions and involves the biological conversion of nitrate into nitrogen gas (N_2)Although it can be an intermediate result of either process, denitrification is more frequently linked to NO_2 [14,26].

Following a thorough analysis of N_2O emissions in WWTPs, Vasilaki et al. determined four key operational elements that are responsible for the production of liquid N_2O in traditional nitrification-denitrification systems. First, they observed that insufficient dissolved oxygen

(DO) in aerobic compartments can lead to nitrite (N_2O^-) accumulation and changes in ammonium (NH_4^+) content, which in turn can promote N_2O formation. Second, they emphasized that the buildup of N_2O^- in anoxic bioreactors and a low chemical oxygen demand (COD) to nitrogen ratio can both lead to the production of N_2O. They also mentioned that one element that can worsen N_2O emissions is the alternating circumstances between anoxic and aerobic environments in intermittent compartments. Finally, they stressed that sudden changes to the process can have a big effect on the creation of N_2O. Dynamic reactions can result from the complex interactions between these variables in bioreactors, which frequently happen outside the operational control. Moreover, they noticed that some of the liquid N_2O generated by different pathways can be consumed by heterotrophic denitrification. The stripping process is still a major source of N_2O emissions from WWTPs notwithstanding the various processes involved in N_2O production and consumption [16].

While the primary source of N_2O emissions in WWTPs is direct emissions from bioreactors, minor emissions also occur from other units within the facility. Hwang et al. measured different sections of a WWTP and found that the digester produced small amounts of N_2O (0.012 g N_2O/kg TN), which constituted less than 1% of the total N_2O emissions. Emissions from primary and secondary clarifiers ranged from 0.22 to 0.26 g N_2O/kg TN. Solís et al. used an EF of 0.01 kg N_2O–N/kg TN to estimate direct N_2O emissions from uncovered sludge storage over the year. Caniani et al. [42] discovered significant findings in the disinfection unit, where a notable N_2O EF of 0.008 kg CO_2e/kg COD was observed due to interactions between the disinfectant and NH_2OH [16].

Tribe [69] examined carbon emissions from WWTPs with varying ammonia discharge levels using tertiary nitrifying trickling filters. The specific carbon emissions were approximately 2.2 tCO_2e/ tNH_3-Nremoved for an ammonia discharge of 5 mg/L through nitrification. This emission rate increased by nearly 50% for an ammonia discharge of 1 mg/L. Over a 40-year lifespan, a WWTP serving 200,000 population equivalents would produce around 455,908 tCO_2e (11,398 tCO_2 annually). The study found that these emissions were primarily due to indirect carbon emissions from electricity consumption and onsite generation [30].

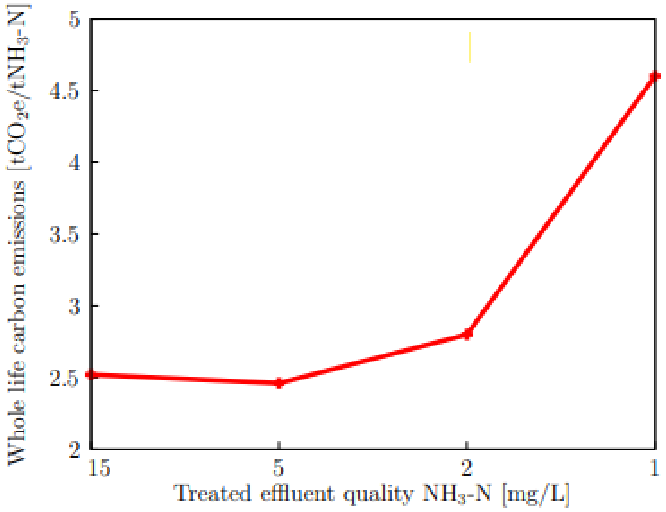

Figure 8: Whole life carbon and effluent quality for tertiary WWTPs [34]

As it can be seen from above explanations there is considerable variability in measured N2O levels both among various treatment plants and within the single plant over time. This emphasizes how important it is to have continuous local measurements to identify the appropriate measures [14].

1.3.3. Identification of GHG emission sources in WWTPs

Predicting GHG emissions from WWTP has gained attention recently as a way to improve sustainability and insights into carbon flow in WWTPs. GHG quantification has grown in importance and offers important information about carbon flow in WWTPs. The design, operation, and optimization of WWTP processes must all take GHG emissions evaluation into account [35]. Among various options, plant-wide mathematical modeling stands out as a viable strategy that can help us better understand how operational and control measures affect GHG emissions as well as improving to environmental protection and lowering GHG emissions. Three sources typically account for GHG emissions in WWTPs: direct, indirect external, and indirect internal [20,30].

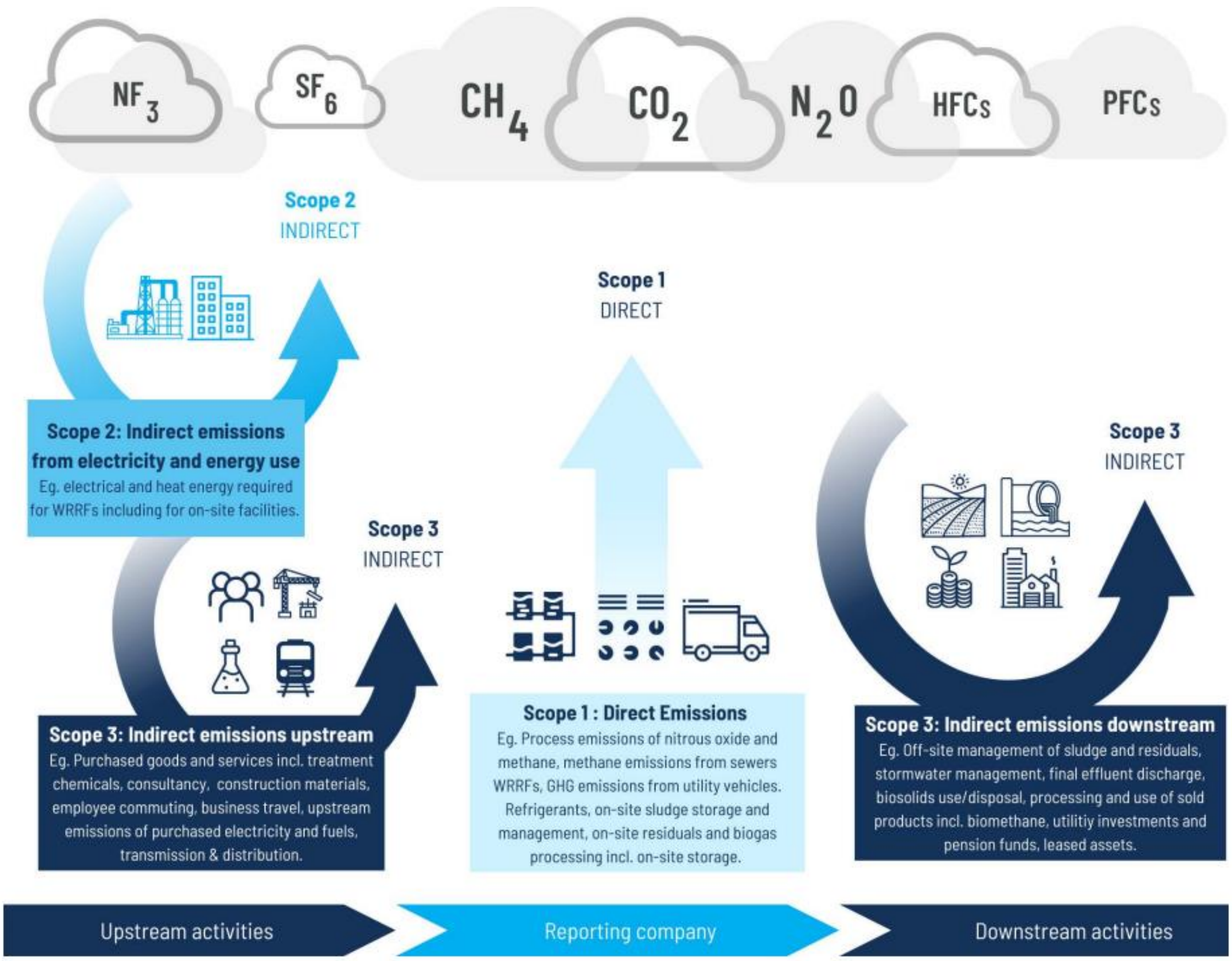

Figure 9: Examples of activities that fit under Scope 1, 2, and 3 emissions categories [21]

Table 4 provides a detailed breakdown of the contributions to the total CF from various sources within WWTPs. It highlights the percentages of GHG emissions from different scopes: Scope 1 includes direct emissions from bioreactors, AD, recipients, and sludge handling, while Scope 2 and Scope 3 cover indirect emissions such as energy use, grit and screening handling, chemicals, third-party sludge handling, and transport [16]. This data from several studies, shows significant variability in emission sources and following the table these 3 scopes will be investigated with detail

Table 4: Distribution of CF Contributions from Various Sources in WWTPs

Reference	Scope 1					Scope 2	Scope 3				
	Bioreactor	AD	Recipient	Sludge handling	Total		Grit and screening handling	Chemicals	Sludge handling (3rd parties)	Transport	Total
[92]	42.9	26.3	9.1	–	78.4	15.5	–	4.2	–	1.7	5.8
[94]	29	–	–	–	29	26	–	–	45	–	–
[95]	58	3	1	10	72	26	1	–	1	–	2
[93]	52	1.5	2	11	66.5	18	0.5	8	–	7	15.5
Min	29	0	0	–	29	15.5	0	0	0	–	0
Max	58	26.3	9.1	11	78.4	26	1	8	45	7	15.5
Average	45.5	4	4	10.5	61.5	21.4	0.8	4.4	15	2.9	17.1

1.3.3.1.Direct emissions (Scope 1) :refer to emissions generated on site as part of an industrial process. They usually take place in the processes involving biological activities which results from fugitive emissions originating biomass respiration, as well as the release of biogas from digesters or gas lines during the treatment of sludge and wastewater. [19,30,16]

Because the direct CO_2 emissions from wastewater treatment are biogenic, meaning they come from the organic molecules in the wastewater breaking down, they are considered as carbon neutral. This is not the case for industries like energy and transportation, where CO_2 derived from fossil fuels contributes significantly to GHG emissions. However, CH_4 and N_2O are two non-CO_2 direct emissions and because of their high GWP, raise serious concerns. The wastewater treatment sector is recognized for its substantial contribution to CH_4 and N_2O emissions, estimated at 7–10% for each gas. Nevertheless, these percentages may fluctuate depending on site-specific elements like plant size, regional variations including climate conditions as well as treatment technology such as unit process and biogas recapturing in the plant as discussed previous section about energy consumption [16].

These emissions caused by various reactions that take place in both the water and sludge lines, occurring under aerobic, anoxic, and anaerobic conditions [15].

Studies indicate that over 60% of the total CF is due to direct emissions and up to 92% of direct emissions originate from aeration tanks in WWTPs [42,19]. This result aligns with extensive literature indicating that the wastewater treatment process is the main source of direct GHG emissions [13,63,65]. In anoxic biological treatment conditions, the production of

CH_4 and N_2O is significantly reduced compared to aerobic conditions [19]. An extensive study by Wu et al. determined that scope 1 emissions account for between 23% and 83% of the overall CF, depending on the specific scenario [16].

1.3.3.2. Indirect internal emissions (Scope 2) :These emissions originate from the usage of obtained or purchased electric/thermal energy. And to evaluate these emissions a national average CO_2 eq emission factor per kilowatt generated is computed. This factor is then multiplied by the number of kilowatt hours used by the facility to determine the overall emissions associated with the energy consumption [30,16].

They are contributing around 20% of the total CF on average. In nations like Finland and Austria that rely heavily on renewable energy sources, these emissions are less significant.

However, Hu et al. discovered a distinct distribution in China, where sludge management significantly contributed 45% of the total CF, compared to a lesser proportion of 29% for direct emissions. This larger percentage was caused by the fact that a sizable portion of the investigated WWTPs were landfilling and incinerating sludge. In factories that do not produce energy on-site, indirect emissions become more significant and account for a majority of the emissions. Table 4 illustrates the wide range of contributions that scope 2 emissions in wastewater treatment facilities (WWTPs) can make, from 14% to 68% of the overall carbon footprint (CF) [19].

1.3.3.3. External indirect emissions (Scope 3) The remaining indirect emissions, are linked to the transportation and production of chemicals outside the plant and the disposal of sludge that are not directly under the control of the plants. These emissions are excluded from the computation of an organization's carbon inventory in order to avoid double counting emissions, which occurs when the same emissions are reported by multiple entities [16,19,30].

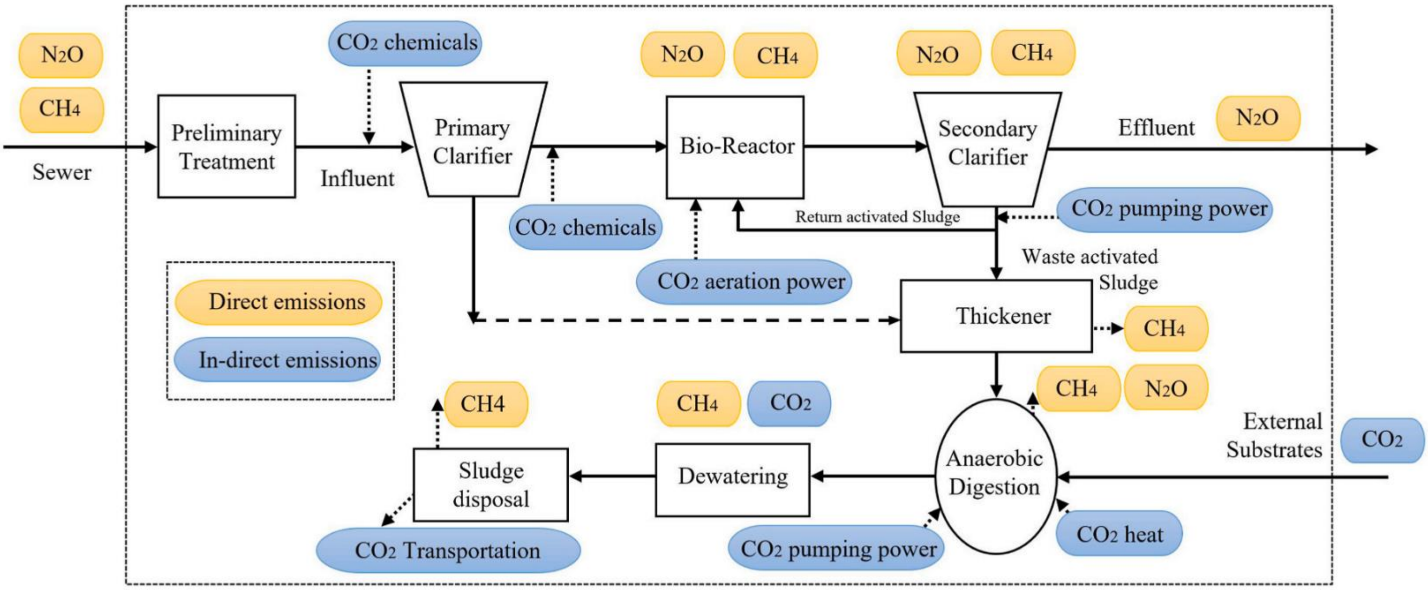

Figure 10: Sources of the direct and indirect GHG emissions in WWTPs [16]

The diagram summarizes an overview of emission sources and energy consumption in WWTPs. Direct emissions encompass N_2O and CH_4, while indirect emissions are primarily CO_2 related to the use of chemicals, aeration power, and pumping power. Emission sources start with preliminary treatment, where sewer systems can release CH_4, especially at headworks and aerated grit chambers. The primary clarifier stage involves CO_2 emissions from chemical use. Bioreactors, which account for 90% of N_2O production, are significant GHG sources in WWTPs and also contribute methane emissions. Secondary clarifiers produce N_2O and CH_4 emissions, as well as CO_2 from pumping power. The thickener stage adds to CH_4 emissions by processing waste activated sludge. Anaerobic digestion (AD) is a key methane emitter (over 70%), with CH_4 generated under anaerobic conditions and CO_2 emissions from pumping power and heat. Dewatering stages release CH_4 and CO_2 due to mechanical sludge processing, while sludge disposal results in methane and CO_2 emissions from transportation. The effluent discharge stage can lead to further CH_4 emissions in natural receiving environments because of the BOD load.

2. LITERATURE REVIEW

Since WWTPs have significant role in energy usage and GHG emissions, the emphasis on energy efficiency and sustainability of them in literature studies has increased. They are investigated in this part into two sections:

1. Energy Optimization in WWTPs; This section examines the energy consumption in wastewater treatment highlighting opportunities for enhancing energy efficiency through equipment upgrades, retrofits and the adoption of high efficiency technologies. It discusses strategies such as optimizing aeration and pumping systems as integrating renewable energy sources like biogas, solar power and wind power. Successful projects for energy optimization are showcased along with their impacts on expenses and energy savings.

2. Greenhouse Gas Emission Reduction in WWTPs; This section investigates the sources of GHG emissions in WWTPs and strategies for mitigation. It focuses on process adjustments such as source separation systems, aerobic granular sludge and anaerobic ammonia oxidation. Additionally, it addresses recovery systems for phosphorus and nitrogen optimization of energy use reduction in chemical usage, transportation efficiency improvements and innovative methods for harnessing N_2O recovery as an energy source.

By synthesizing insights from different studies this literature review aims to offer an overview of progress made and challenges faced in enhancing the energy efficiency and environmental sustainability of WWTPs.

2.1. ENERGY OPTIMIZATION IN WWTPS

Wastewater treatment consumes about 35% of the energy used by a municipality for heating, cooling, and street lights [59]. And recently, the focus on energy efficiency has become crucial for promoting sustainability. Moreover, enhancing energy efficiency presents a significant opportunity to improve rising energy consumption while also enhancing wastewater treatment processes [30].

For instance, a domestic WWTP using activated sludge and anaerobic sludge digestion uses about 0.6 kWh/m^3, primarily from air supply for the activated sludge. However, this energy consumption can be decreased by 25–50% by using biogas from anaerobic digestion. Plant design changes have the ability to drastically reduce energy consumption, turning wastewater into a net energy producer as opposed to a consumer [36].

Water and sewage facilities consume considerable energy, constituting approximately one-third of municipal energy usage. Identifying different opportunities to improve energy efficiency is critical to diminish energy usage at WWTPs [59]. These technologies may be sorted according to a number of factors including their structure, management, and effectiveness [30].

2.1.1. Equipment Replacement and Retrofitting

It is practically necessary to assess equipment on a frequent basis with respect to its status, performance and remaining lifespan. Aging equipment, having reached its operational limit, typically consumes more energy than new ones. While acquiring new equipment demands initial investment, the long-term energy savings could outweigh the costs [30].

Enhanced equipment functions with greater efficiency compared to standard models, providing equivalent service while consuming less energy. It also provides better control options and allows for demand-based usage to minimize wastage [58].

Previous equipment designs likely incorporated various assumptions, including adherence to design standards, engineering knowledge, worst-case scenarios and safety margins, often resulting in oversized systems. As a result, activities may differ greatly from ideal conditions. Energy costs can usually be lowered by 5–15% by replacing outdated pumps with higher efficiency models. For example, East Bay Municipal Utility District (EBMUD) in California implemented various energy-saving measures, such as consolidating compressors and upgrading motors with variable frequency drives (VFDs), resulting in a substantial 50% decrease in pump electricity consumption [30].

2.1.1.1. Utilizing Efficient Equipment

In the previous section it was noted that aeration and pumping consume significant amount of energy in WWTPs, highlighting the importance of finding ways to optimize their energy usage which will be discussed in this section. Additionally in Table 5 provided below various opportunities for energy optimization are listed along with actions to save energy. These optimization possibilities may vary for each facility underscoring the need for an energy assessment to identify the effective cost efficient and advantageous strategies tailored to each specific facility's needs [59].

Table 5 : Energy Optimization Areas in WWTP [59]

Area	Action for Energy Optimization
Aeration	Install automatic DO control on aerators
	Variable Speed Drives (VSDs) on mechanical aerators or aeration blowers
	Convert to diffused air aeration
	Convert from coarse to fine bubble aeration
	Reduce air pressure when possible
	Consider anaerobic and deep well treatment technology
Pumping (General)	Install VSDs on pumps with long run hours and that are throttled or have Bypasses
	Run pumps in parallel
	Reduce pressures where possible
	Install improved efficiency motors/pumps/valves
	Downsize where oversized
Lift Stations	Install VSDs on pumps
	Install improved pump controls
	Install improved efficiency pumps/motors/valves
	Vary well levels to reduce loads, especially during peaks
Sludge Handling and Disposal	Install VSDs on sludge pumps
	Improve dewatering before incineration
	Install VSDs on incinerator fans
	Consider land disposal or pelletizing vs incineration
Reducing Peak Load	Consider self-generation at system peaks
	Schedule pumping during lower cost periods
	Identify loads that can be reduced or interrupted
	Consider more storage

One strategy is high-efficiency motors which are designed to use energy more effectively and have a higher power factor, requiring less maintenance and providing greater reliability. They are especially cost-effective for high-capacity applications. Their superior performance results from design improvements, precise manufacturing, and materials like low-loss steel, thinner stator laminations, and more copper in the windings. Enhanced bearings and aerodynamic cooling fans further boost efficiency [58].

In wastewater treatment, pump and blower motors account for 80% to 90% of energy costs, with lifetime energy costs being 10 to 20 times the initial motor cost. Therefore, high-efficiency motors significantly reduce operating expenses. The subsequent section provides a detailed examination of these technologies [58].

2.1.1.2. Energy Efficient Pumping

Enhancements in energy efficiency have the potential to decrease electricity usage for pumping by around 5%-25%, and sometimes even more. To create an efficient pumping system, it is essential to follow a series of steps:

-Choosing the right pump

-Adjusting the flow rate through control

-Using pumps in parallel for variable demand

-Implementing start/stop pump control

-Impeller trimming

-Eliminating flow control valve

-Eliminating by-pass control system

a. Choosing the right pump: Choosing the appropriate pump involves a careful review of a pump performance curves and a comprehensive analysis of various parameters to ensure that it meets system requirements. The selection should prioritize the available head and flow rate. The pump's operational point is found at the intersection of the system curve and the pump performance curve, which are both created using numerous duty points (flow rates at particular heads), as shown in Figure 11 [59].

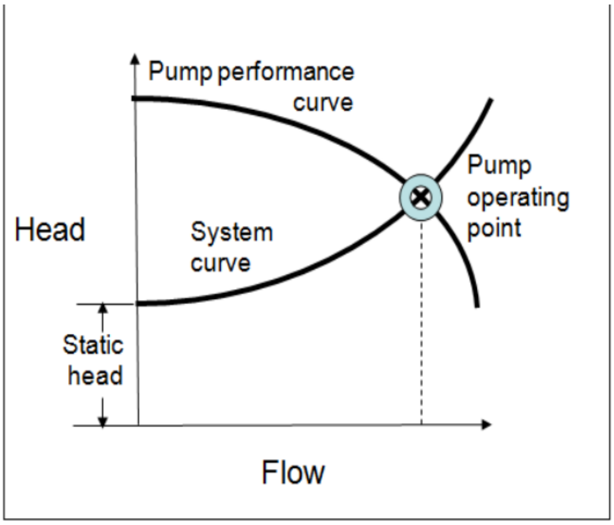

Figure 11: Pump Performance curve

The system curve illustrates the relationship between pressure and flow rate in a piping system. When the pump is oversized, it shifts this curve to the left, resulting in operation at lower flow rates and higher pressures than ideal. This leads to a decrease in pump efficiency, as it moves away from its Best Efficiency Point (BEP), resulting in reduced output flow while maintaining constant power consumption. To mitigate these issues, there are actions that can be taken. One option is to install trimmed impellers that better suit the required flow conditions and improve efficiency. Another solution is to use speed drives (VFDs) so that the pump can run at speeds while maintaining efficiency under various conditions. Furthermore, utilizing two speed drives or motors, with lower RPMs can optimize performance by adapting to specific flow needs. By implementing these strategies pump efficiency and overall system performance can be greatly enhanced, leading to reduced energy consumption and operational expenses [59].

b. Adjusting the flow rate through control

Flow rate and head are two aspects of pump performance that change as rotational speed changes. To effectively manage the pump, comprehending the following correlations is crucial:

- Flow rate (Q) increases proportionally with rotational speed (N).
- Head (H) rises proportionally to the square of rotational speed.
- Power (P) increases proportionally to the cube of rotational speed.

These relationships demonstrate that when the pumps rotating speed doubles there is an eight-fold increase in power usage. On the other hand, even a slight speed decrease can lead to significant energy savings. This principle supports the energy conservation in pumps with fluctuating flow needs [59].

Gravity flow is the best way to move wastewater to treatment facilities in many wastewater treatment systems, but it's frequently not practical for a variety of reasons. As a result, influent pumping becomes necessary involving the use of high capacity pumps at lift stations to provide the head for water to reach the treatment plant.

These pumps, which frequently have high head and flow rates, call for energy-saving solutions like variable frequency drives (VFDs) and premium efficiency motors. VFDs offer the most efficient means of regulating pump speed. Additionally, they enhance system consistency and minimize maintenance expenses

Unlike mechanical devices with variable flow, VFDs allow pumps to adapt to changing needs, resulting in significant energy savings of up to 50%.

They are superior to conventional single-speed motors in terms of torque, control accuracy, and upkeep needs, which leads to increased motor longevity and efficiency. Although the effectiveness of VFDs hinges on factors such as pump size and static head, they generally offer reliability, user-friendliness, and contribute to decreased energy expenses and noise levels in wastewater treatment facilities [58].

This pump is also applicable in tertiary treatment and sludge processing steps. Tertiary treatment involves creating an anoxic environment within the secondary treatment system and includes processes like filtration, activated carbon treatment, ion exchange, and membrane filtration where using power of pumps are essential. Therefore, using VFDs and premium efficiency motors for these pumps is an option to improve energy efficiency. Sludge processing is an intricate procedure that encompasses several steps. VFDs and high-efficiency motors are among the energy-efficient choices available for thickening, stabilization, and dewatering [58].

c. Using pumps in parallel for variable demand :Operating multiple pumps simultaneously and deactivating some during periods of reduced demand can lead to notably cut down usage and enhances pumping efficiency [59].

d. Implementing start/stop pump control : Pump start/stop control is a good approach to maximize energy as long as it is not overused. This method helps leverage of non-peak periods to reduce the workload on the pump, as a result use less energy.

*e. Impeller trimming :*In order to effectively manage flow rate, changing the impeller diameter is crucial, however it must be done within specified limitations to maintain pump efficiency. Reducing the impeller diameter should not exceed 25% of the initial size to avoid cavitation-induced vibration, which can lead to reduction in efficiency of the pump. Moreover, it's crucial to maintain symmetry by ensuring trimming of the impeller, on all sides.

f. Eliminating flow control valve :Implementing flow control valves diminishes efficiency by amplifying friction and head loss. Shutting the control valve elevates the head without decreasing power consumption. Additionally, control valves cause vibration and corrosion, thereby shorten the life of pumps and reduces their efficiency.

g. Eliminating by-pass control system :By-pass control divides the pump's output into two flows that go into two different pipes, while the first pipeline transports the water to the distribution location the second pipeline returns the fluid to the source where a portion of the fluid gets pumped around pointlessly and cause energy lost. Consequently, it is necessary to remove the by-pass control system.

Aside from that, energy-efficient pumping can be achieved through various other methods. Utilizing computer systems like SCADA and Telemetry for pump operation and maintenance is one such method. These systems continuously monitor flow rates, head, and pump performance, enabling operators to make real-time adjustments for optimal operations [58,59].

2.1.1.3.Efficient Wastewater Aeration Systems

Aeration process accounts for 50-70% of the total energy used by the plant and is the second-highest operational expense after labor. The process creates an aerobic atmosphere essential for microbial breakdown of organic waste. The two main goals of aeration are to give the metabolizing microbes the oxygen they need and facilitate mixing ensuring that microorganisms are in the contact with the suspended and dissolved organic matter [59]. While this process consumes a significant amount of energy, it lowers the ammonia concentration in effluent which is beneficial for water quality. However, this raises a question of whether there could be a better balance between the consumed energy and quality of effluent. According to sensitivity analysis, among major operational variables of this process, the dissolved oxygen (DO) set-points and, to a lesser extent, the sludge retention time (SRT) have the greatest impact on aeration energy.

It is proposed that adjusting the DO set-point and SRT depending on the nominal condition could potentially reduce energy consumption by up to 10-20%. On the other hand, due to partial nitrification or denitrification these adjustments may result in increased N_2O emissions [30].

Figure 12 illustrates how different DO set-points—which are assumed to be the same in both wastewater and sludge treatment lines—affect consumption of energy, discharge of total nitrogen (TN) and ammonia and emission of N_2O. For example, a 15% reduction in aeration energy can be achieved by lowering the DO set-point from 2 mg/L to 1 mg/L, with little effect on ammonia discharge and a minor decrease in TN discharge. Reducing the DO set-point to 0.5 mg/L while maintaining the ammonia effluent concentration below 0.2 mg/L will result in further reductions in TN effluent concentration and aeration energy. On the other hand, operating at a low DO set-point can have unfavorable consequences such as higher emissions of nitrous oxide (N_2O) as a result of incomplate nitrification, which could enhance climate change. N_2O emissions increase significantly as the DO set-point decreases, by a factor of 3 between 0.5 mg/L and 2 mg/L. It's crucial to remember that, even though the model does not take this into account, operating at a low DO set-point may also have unfavorable consequences on treatment quality, such as poor sludge settleability. Therefore, finding the optimal balance between energy consumption and effluent quality requires careful consideration of various operational parameters [30].

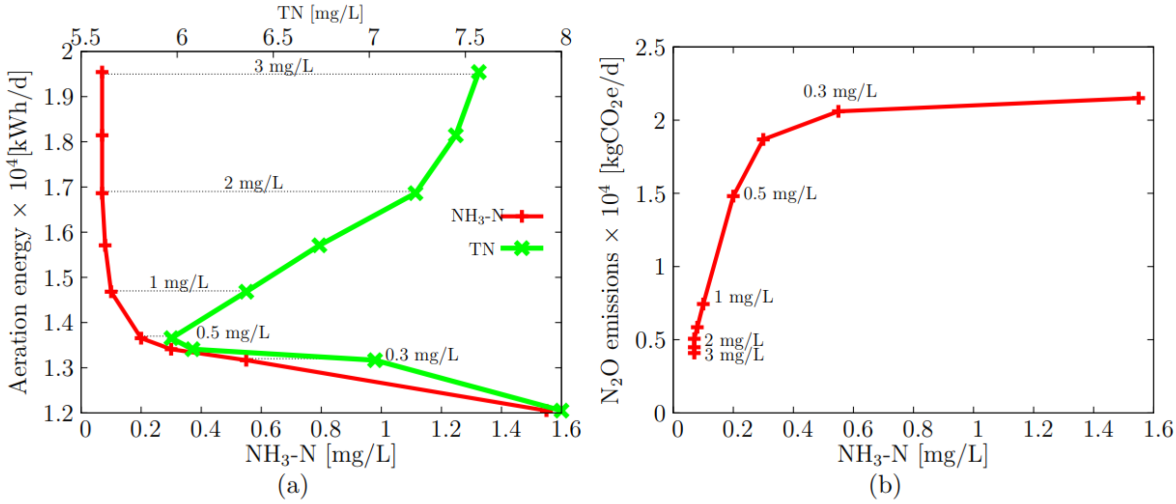

Figure 12: Effect of DO set-points on (a) the aeration energy, effluent quality (NH3-N represented by the red line and TN represented by the green line) and (b) N2O emissions (The concentrations in figure (3 mg/L, 2 mg/L, 1 mg/L, 0.5 mg/L and 0.3 mg/L) indicate the DO-setpoints). [30]

In the same investigation, the impact of altering the SRT on energy usage, TN discharge, and N_2O emissions was studied (Author et al., Year). By reducing the SRT (Figure 13a), and therefore the level of endogenous decay, it is possible to lower the aeration energy by a small percentage. However, this also increases the energy and cost of sludge treatment. A decrease in the SRT is similarly correlated with a rise in N_2O emissions (Figure 13b); however, this rise is negligible in comparison to the GHG emissions resulting from the associated energy consumption.

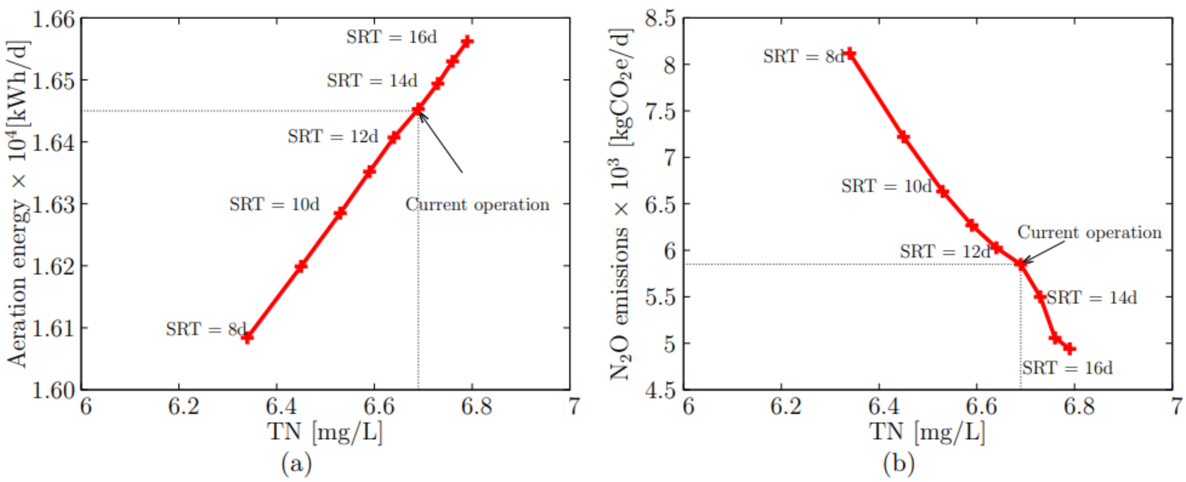

Figure 13: Effect of SRT on (a) the aeration energy, effluent quality and (b) N_2O emissions. [30]

The three main technologies that can significantly reduce the energy consumption of a wastewater aeration process are as follows:

a.Diffuser Technologies:

Coarse or medium bubble aerators are used commonly especially in older plants because they are less expensive and less prone to foul from air flow impurities or wastewater exposure. For coarse-bubble diffusers, the usual oxygen transfer efficiency is between 9-13% On the other hand fine bubble aerators cost more, need cleaner air, and need to be cleaned more frequently. Nonetheless, they are thought to be the most effective oxygen transfer system in WWTP, providing an oxygen transfer efficiency of 15% to 40% since they have a larger total surface area, produce more friction, and rise more slowly than coarse bubbles and within this properties, they are cost-effective because their power costs can be lowered by up to 50% [58,59].

Upgrading from coarse bubble diffusers to fine bubble diffusers typically results in energy savings for aeration systems ranging from 20% to 40%. Despite the higher initial investment costs for fine-bubble diffusers, associated piping, tankage, and gas transfer domes, as well as increased maintenance and cleaning expenses, these retrofits often achieve a return on investment within 2 to 4 years [58].

In Table 6, typical oxygen transfer rates in clean water are displayed whereas Table 7 shows some alpha values that can be used to calculate the relative rate of oxygen transport in wastewater as compared to clean water. Due to the components of wastewater, beta value offers a correction for oxygen solubility and this value for municipal wastewater is between 0.95 and 1 [61].

Table 6: Typical Clean Water Oxygen Rates [61]

Diffuser Type and Placement	**Oxygen Transfer Rate (lb O_2/hp-hr)**
Coarse Bubble Diffusers[1]	2
Fine Bubble Diffusers[2]	6.5
Surface Mechanical Aerators	3
Submerged Turbine Aerators[3]	2
Jet Aerators[4]	2.8

[1] For 2.7 - 3.6 m (9-12 feet) submergence

[2] For 18 - 26 W/m^3 (0.7-1.0 hp-hr/100 ft^3)

[3] Includes both blower and mixer horsepower

[4] Includes both blower and pump horsepower

Table 7: Typical alpha values for wastewater [59]

Diffuser Type and Placement	Typical Alpha (α)
Coarse Bubble Diffusers	0.8
Fine Bubble Diffusers	0.45
Surface Mechanical Aerators	0.85
Submerged Turbine Aerators	0.85
Jet Aerators	0.75

Based on the Table 7**,** fine bubble diffusers are the most efficient for oxygen transfer, however, they have a lower alpha value, indicating reduced efficiency in wastewater. Surface mechanical aerators and submerged turbine aerators both maintain high efficiency in wastewater. Therefore, it can be said fine bubble diffusers are best for maximum efficiency, while surface mechanical aerators are optimal for consistent performance in wastewater conditions. On the other hand, **c**ourse bubble diffusers and jet aerators provide lower efficiency but may be suitable for cost-sensitive applications.

*b.Blower Technologies***:**

The selection of aeration blowers plays a role in determining the energy consumption of any WWTP. Bell et al. conducted an analysis on the relationship between energy savings, pressure ranges and airflow rate associated with aeration blowers used in WWTPs. It was discovered that the efficiency for single-stage centrifugal blowers, multi-stage centrifugal blowers, positive displacement blowers and turbo blowers was 65%–80%, 60%–75%, 45%–60% and 70%–85% respectively [17].

Positive displacement blowers are typically utilized for lower flows or in situations where the discharge pressure is greater than 8 to 10 psi, while centrifugal blowers are typically employed for higher flows [58].

There are two varieties of centrifugal blowers: single stage and multistage. In comparison to single stage units, multistage centrifugal blowers are less efficient and have restricted turndown capability (around 70%). Adjusting the flow while keeping the impeller speed constant is possible with single-stage blowers equipped with variable inlet vanes and variable-discharge diffusers and they can perform 40-80 compression efficiency. Although they can be ignored, they have a few drawbacks, like their high cost [58].

*c. Air Control Technologies***:**

An automated control system has the greatest energy-saving impact on a facility, even though the kind of aeration system used is crucial for providing air efficiently. The most popular tools for measuring the amount of dissolved oxygen in wastewater and producing a variable signal to change air flow, aerator speed and tank level in aeration systems are dissolved oxygen probes and analyzers [59].

Single-point and double-point control systems are available in centrifugal blowers. However, because of the intake losses connected with throttling, single-point control technology drastically lowers system efficiency and therefore less appropriate for WWTP applications, even though it is successful at controlling total capacity. Conversely, double-point control technology employs a multi-variable control mechanism to provide independent regulation of the head and flow functions. This approach keeps base efficiency close to maximum in a variety of flow and temperature scenarios. Compared to other technologies, using a single-stage centrifugal blower with double-point control technology can minimize aeration system power consumption by 30–50% [59].

Comprehensive Review of Aeration Optimization Strategies for Energy Efficiency in WWTPs

The wastewater treatment industry has made various efforts to optimize aeration by controlling DO setpoints, given that aeration is highly energy-intensive. For instance, Amand et al. explored a method to control aeration to cut energy use while meeting effluent discharge standards. Their study indicated that airflow requirements could be reduced by approximately 1-4% compared to a constant DO setpoint, and by 14% compared to rapid feedback on effluent ammonium, by altering control and operational strategies [51].

In the other study conducted by Borzooei et al. they developed an integrated modeling platform that connected wastewater treatment processes, energy demands, and production sub-models. The study uses simulations of aeration systems alongside proportional integral (PI) controller to adjust airflow based on DO levels in order to be sure that the aeration process meets the actual oxygen requirements. By setting the SRT to 25 days the research achieves an equilibrium, between energy usage and effluent quality. Moreover, by creating energy consumption sub models for aeration pumping and mixing operations additional opportunities for optimization are identified. An energy assessment implementing the suggested modifications could lower energy usage from 0.3 kWh/m³ to 0.28 kWh/m³ resulting in savings of up to 5000 MWh/y [4].

Liu et al. (2011) conducted a study on the OTE and the economic costs associated with aeration systems in a municipal WWTP in China. The research examined the SOTR of both new and old aerators, discovering that the SOTR of **old aerators** had significantly decreased due to damage and blockage of the micro-porous membranes. The study concluded that replacing old aerators, which had been in use for over a decade, could result in annual savings of approximately 0.9 million Yuan, with a payback period of just 14 months. When this amount is compared with old electricity cost of the plant the percentage of electricity consumption reduction in overall plant is calculated as 10% [43].

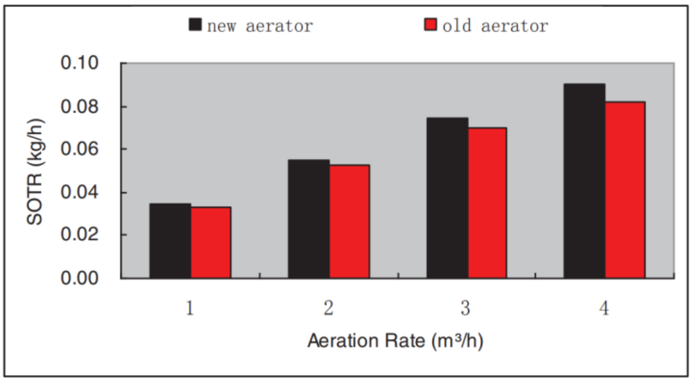

Figure 14: Test result of SOTR between new aerators and old ones

Drewnowski et al. (2019) conducted an examination of aeration system design specifically focusing on blower aeration and the effectiveness of bubble diffused aeration. They investigated factors influencing OTE, such as wastewater composition, diffuser fouling, diffuser depth and airflow rates. The research explored strategies to mitigate diffuser fouling, including the application of formic acid and high pressure cleaning. The team also introduced control systems that integrate mathematical models and sophisticated control techniques like model predictive control (MPC) and ammonia based aeration control (ABAC). These systems were tested at the "Dębogórze" WWTP, where the implementation of SCADA system led to a 15% -25% decrease in energy consumption [45].

Daw et al. conducted a study, on the electricity consumption at the WWTP in Colorado. They analyzed the energy usage before and after optimizing it for each process unit. One notable change they made was connecting a DO sensor to the plants SCADA system, which allowed the aerator to automatically turn off when the DO concentration reached a level. This modification resulted in an energy saving of 123,000 kWh leading to a 40% reduction in electric energy consumption [52].

Poyry et al. (2021) created a model to estimate the energy needed for aeration in WWTPs, focusing on control valve positions and blower operations and suggested potential improvements. Their proposed way to enhance the system by adjusting one parameter providing estimates of energy usage even with limited data. The research highlighted the crucial role of control valve positioning in influencing power consumption and airflow distribution. The model allowed for comparisons between different blower and valve setups and suggested potential improvements in aeration control strategies. Results showed that a 2.2% reduction in backpressure setpoint could result in a 15% decrease in energy consumption which shows significant potential for energy savings [48].

Abulimiti et al. (2022) explored the balance between nitrous oxide (N_2O) emissions and energy savings using dynamic simulation to evaluate aeration control strategies in a full-scale WWTP. The study revealed that N_2O emissions are highly variable and better captured through dynamic simulations. Various DO control strategies were tested, including ultralow-oxygen (0.2–1 mg/L) and low-oxygen (1–2 mg/L) intervals, to optimize energy use and GHG emissions. The findings indicated that the ultralow-oxygen strategy with high-frequency control achieved the lowest GHG emissions under current energy conditions, reducing emissions by 5.5% compared to the actual state. In contrast, for the year 2050 considering cleaner energy mix, suggested that overall GHG emissions with the ultralow oxygen approach would surpass those with low oxygen aeration by 3.6-4.2% [46].

Mamais et al. evaluated 10 WWTPs with capacities ranging from 10000 to 4000000 PE in Greece and offered strategies for reducing their energy usage and GHG emissions. The findings emphasized that adjusting DO set points and optimizing SRT could lead to reductions in both energy usage up to 11.2% and GHG emissions. [66].

Chen et al. (2022) introduced a method to improve energy efficiency during the aeration process. By using the Lawrence McCarty principles they developed a model focusing on DO sludge discharge quantity (QW) as key factors. Through an optimization algorithm they adjusted DO and QW rates to enhance energy efficiency, which was confirmed using real time data from a WWTP. This optimized strategy resulted in 20% energy savings during aeration. By improving blower efficiency from 74.5% to 90% electricity consumption could be further reduced by 17.2% [49].

Similarly, Azis et al. (2019) employed the HYBAS system and revealed that substituting roots blowers with high speed turbo (HST) compressors had an impact on diminishing energy consumption in a WWTP in Malaysia. The results pointed out that the HST blower reduced energy usage by as 42% corresponding to 199400 kWh/y energy saved and offered a swift return on investment in just 1.22 years [47].

Larsson examined the energy savings achieved by implementing a new aeration and control system at the Sternö WWTP in Sweden, which serves 26000 PE. The installation included an screw blower and fine bubble diffusers on one of the two parallel biological treatment lines. They discovered that new blower reduced energy consumption by 35% and the diffusers added another 21% in savings. Moreover, fine tuning controllers resulted in a further 9% reduction. On the other hand, it was also found that controlling ammonia levels did not have a significant impact on energy usage. Altogether the energy saved amounted to around 65% (178 MWh) which is 13% of the plants energy consumption. The payback period of the new system was estimated to be around 3.7 years [50].

The Environmental Protection Agency (EPA) released a study on efficiency improvements in different WWTPs. The study emphasized that reducing aeration amount, automating aeration processes or upgrading blowers were proven strategies for saving electricity. The Orange County WWTP adopted energy saving initiatives such as refurbishing blowers and enhancing control systems, which resulted in a savings of 792 kilowatts. Similarly In Los Angeles, reducing the operation of aeration blowers when not necessary led to a 34.3% saving in total electricity consumption [53]. The WWTP in Franklin showcased energy savings through the use of DO controls and upgrading their blowers. By replacing their blowers with high-speed direct-drive turbo blowers equipped with permanent magnetic motors they managed to reduce aerations energy consumption percentage from 36% to 32%. A study conducted also compared the estimated energy amount of three different aeration blower options; centrifugal blowers running at 4000 cubic feet per minute (cfm) consumed 1500000 kWh/year, turbo blowers at the same rate used up 920000 kWh/year and slightly smaller turbo blowers operating at 3400 cfm utilized only 780000 kWh/year. Switching to turbo blowers alone is predicted to result in a reduction of overall electricity consumption by about 17% whereas implementing automatic DO control on its own is expected to lead to a decrease, in electricity usage ranging from 15% to 20% [54].

Machine learning (ML) is an emerging approach for lowering the energy requirements of WWTPs. Cao and Yang created the OS-LEM model to regulate dissolved oxygen (DO) supply in aerobic bioreactors, achieving a 40% reduction in energy use compared to traditional on/off DO control methods. Similarly, Ramli et al applied ML to develop a predictive model for WWTP energy consumption, which forecasts energy needs one month in advance, resulting in an estimated 2.2% reduction in energy usage [16].

In the detailed study, Wiseman (2020) delves into the energy consumption and GHG emissions associated with aeration systems in WWTPs underscoring the influence of aeration on energy usage. The research demonstrates that implementing control systems and regular maintenance can result in energy conservation. For instance, integrating SCADA systems WWTP in Crested Butte Colorado led to a 40% decrease in energy consumption of aeration saving 123000 kWh annually. Regular maintenance to address diffuser fouling is crucial for maintaining OTE. Additionally transitioning from aeration equipment to high-speed turbo blowers can substantially reduce energy consumption as evidenced by Franklin, New Hampshire’s WWTP experiencing a 32% decrease in electric energy input following the installation of high-speed, direct-drive turbo blowers. Tuning operational parameters like establishing DO set point is vital for create a balance between energy utilization and effluent quality. Insights from laboratory scale model replicating full-scale WWTP operations highlighted improvements in aeration control strategies by enhancing comprehension of the correlation between sensor readings and oxygen inputs. These findings underscore the potential for saving energy and reducing emissions by optimizing aeration systems, in WWTPs highlighting the role of advanced technologies and maintenance practices in achieving these advancements [17].

In their 2023 review, Gu et al explored strategies for optimizing aeration in WWTPs, including aerator design, improved mass transfer and the application of advanced aeration control techniques. Advanced aerator designs include nanobubble technologies known for their high oxygen transfer efficiency. They enhance the interaction, between liquid and gas phases thereby improves the rate of mass transfer. These advancements offer energy savings compared to traditional methods potentially decreasing energy usage by up to 30%.

Another key approach involves improving transfer within reactors. By optimizing bubble size and distribution to maximize area and the liquid phase mass transfer coefficient notable results obtained. Smaller bubbles increase interfacial area while larger bubbles induce turbulence enhancing oxygen transfer efficiency. Such enhancements have demonstrated a 20 30% improvement in oxygen transfer efficiency leading to reductions in aeration energy requirements.

Studies have also emphasized the importance of implementing real-time aeration control strategies based on dissolved oxygen (DO) levels. By adjusting aeration rates according to real time DO measurements, over-aeration can be prevented, leading to reduced energy consumption. This approach can achieve energy savings of 15-25% by ensuring that aeration rates are aligned with microorganisms' actual oxygen demand. [44]

2.1.2. Additional Energy Efficiency Measures

There are also other various ways to enhance energy efficiency in WWTPs as some of the most common ones can be seen below. Implementation of them differ from plant to plant depending on the plant conditions and limitations.

Tertiary Treatment

For nitrogen removal, tertiary treatment often complements secondary treatment by creating an anoxic zone within the secondary system. This process involves the use of filters, activated carbon, ion exchange, and membrane technologies, which are typically pump-driven. Therefore, employing Variable Frequency Drives (VFDs) and high-efficiency motors can be beneficial [58].

UV Disinfection:

Low-pressure UV systems are noted for their higher energy efficiency compared to medium-pressure UV systems. Despite the fact that medium-pressure UV systems offer greater intensity, better penetration, and require fewer lamps which result in lower capital and maintenance costs the energy savings with low-pressure UV can still be appealing if the plant can achieve a satisfactory return on the additional capital and maintenance investments [58].

Sludge Processing:

Sludge processing is intricate and involves multiple steps such as thickening, stabilization, and dewatering. Energy-efficient options for these processes include VFDs and high-efficiency motors. The baseline design for VFD applications in sludge processing must be customized due to the variety of available processing techniques, which include belt filter presses, centrifuges, and anaerobic or aerobic digestion. Liquids extracted from sludge are usually returned to the headworks of the wastewater treatment plant and may be pumped using on/off or pressure-reducing valves, suitable for VFD applications. However, centrifuges and belt filter presses are typically not ideal for VFD use [58].

2.1.3. Renewable Energy Integration and Energy Recovery

Because of WWTPs' high energy consumption, the applications about producing or recovering renewable energy within the plants have increased recently. While biogas production and heat conservation within the wastewater are the main contributors to energy, solar, wind and hydroelectric energy can also be used in some cases.

2.1.3.1.Wastewater heat energy: It is possible to recover the heat energy contained in wastewater and utilize it to both heat WWTPs and a nearby district heating network. Nevertheless, there is little chance of applying the latter one because the majority of wastewater plants are situated far from cities. In WWTPs, stored heat is often used to boost biological activity and wastewater is a suitable heat source because it is usually available in large volumes and flows steadily [30,36].

2.1.3.2.Hydroelectric power: It is an alternative energy source that produce energy from wastewater by using turbines or other equipment which can be located in conduits, such as aqueducts or pipelines. A typical hydroelectric power unit can generate energy with an efficiency of over 70%. Apart from electricity generation, the created turbulent mixing caused by the equipment can also increase oxygen transfer from the atmosphere into the water, enhancing the DO levels in the treated water which will ultimately enhance biological activity, improve treatment efficiency, and help reduce odor and pollution. However, the fundamental difficulty of this technique is that it requires the effluent to have sufficient kinetic or potential energy to make investment feasible [30,76].

2.1.3.3 Solar and wind energy: Electricity can be generated from renewable sources like solar energy. Although a large area is required for solar panels, this need is often met by the expansive footprint of most WWTPs, which are designed to accommodate such installations. The integration of solar panels can leverage the available space, making it easier to install and generate clean energy. However, challenges such as long pool spans, underground pipelines, and construction difficulties have limited the widespread implementation of PV projects at sewage plants. Despite these obstacles, PV systems have been installed above reaction pools in some WWTPs to boost clean power generation and provide thermal insulation. By the end of the 13th Five-Year Plan, PV projects in Xiaohongmen, Qinghe, and Jiuxianqiao WWTPs reached a total capacity of 18.7 MW, with plans to increase by 17 MW by 2025, generating 18 million kWh annually. Bailong WWTP in Shanghai plans to implement a PV system to replace 25% of its electricity consumption with solar energy. However, the initial investment cost for solar panels can be a significant drawback [30,76].

Similarly, wind energy can be harnessed to produce electricity. While many WWTPs are situated at low elevations, which is less ideal for wind energy, the open areas near water can provide sufficient wind flow for turbines. Despite the advantages of wind energy,the considerable costs involved in setting up wind turbines present a challenge [30]

2.1.3.4. Biogas :

Sewage sludge, a by-product of the WWTP process, is rich in pollutants, organic content, and water. This sludge requires treatment before disposal and anaerobic digestion is seen as a promising method. This biological process involves the digestion of organic matter by bacteria, resulting in the production of digested sludge and methane-rich biogas which typically composed of 60–70% CH_4, 30–40% CO_2, 4% nitrogen, and trace elements, can be extracted and converted to thermal or electrical energy. It is simpler to obtain more energy from a plant with a comparatively high influent load of organic matter than low load. Digested sludge can be further dewatered and used as a fertilizer, whereas as a renewable fuel biogas can be used for heating, generating electricity, or upgraded and injected into the gas grid. The multiple benefits of anaerobic digestion such as reducing treatment costs, providing energy recovery and enhancing sustainability make it a widely adopted technology in WWTPs [42,30,72].

Biogas generation process:

Biogas production involves microorganisms converting organic matter into biogas through four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Figure 15) [42].

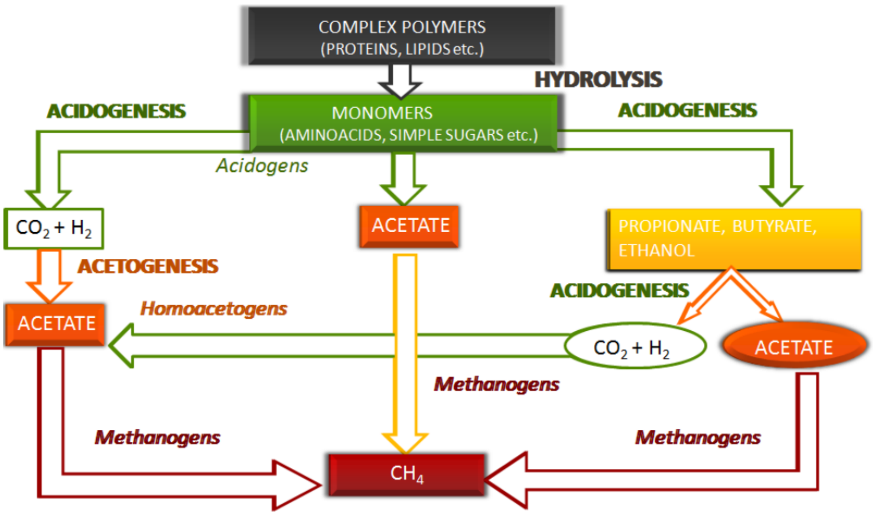

Figure 15: Main steps of biogas production

• **Hydrolysis**: This methods primary goal is to make big molecules simpler. By using enzyme catalysis in hydrolytic bacteria, hydrolysis breaks down complex insoluble organic compounds (like lipids, polysaccharides, proteins, and nucleic acids) into soluble simple organic materials (like fatty acids, simple sugars, and amino acids). [42, 71]

• **Acidogenesis**: The products of hydrolysis are converted into volatile fatty acids, alcohols, ammonia, and hydrogen sulphide by fermentative bacteria [42].

• **Acetogenesis**: Volatile fatty acids and alcohols are transformed into acetate, carbon dioxide, and hydrogen. Most of the carbon dioxide and hydrogen are produced at this stage [42].

• **Methanogenesis**: Methanogenic organisms convert acetate and hydrogen into methane and carbon dioxide. This stage which also known as biomethanation is where waste is stabilized [42].

Factors influencing biogas production

Feedstock parameters, design and operational conditions are the factors that affects anaerobic digestion and biogas production. Since some of these factors can be used as controllable variables in anaerobic digestion models to enhance biogas production, methane yield, and quality of the treated wastewater and digested sludge, it is crucial to understand how they affect the performance [42].

a.Feedstock parameters

In WWTPs, the typical feedstock consists of primary and secondary sludge, often referred as mixed sludge. Greases from the grease trap are also commonly digested. However, screenings are not suitable for anaerobic digestion since contain coarse debris that could damage pumps and stirring systems [73].

In the primary settler, gravity sedimentation yields primary (raw) sludge which is readily degradable and contains a large amount of organic matter. A methane production of 315–400 Nm^3/t organic dry matter (ODM) is anticipated under ideal digestion conditions [73].

Secondary sludge, also known as surplus or activated sludge, is the byproduct of biological treatment. It produces less biogas since it has a smaller degradable content than primary sludge. At ideal digestion conditions, 190–240 Nm^3/t ODM is produced as methane. [73,12,42]

Some of these parameters are explained below [42].

- *Total solids (TS)*: The amount of residues left behind after the feedstock is dehydrated. TS is represented as a percentage (%) and combines the suspended and dissolved solids.
- *Suspended solids (SS)*: Related to the small solid particles that remain suspended in wastewater and typically removed in the primary treatment or by water filters.The quantity of suspended solids is usually high in municipal wastewater.
- *Volatile solids (VS)*: refers to the amount of organic solids in wastewater and is a crucial parameter for assessing a WWTP's effectiveness. VS of the digested sludge ranges from 45% to 50%, while the in the raw sludge might range from 70% to 75%. By 40–60%, anaerobic digestion can lower VS.
- *Volatile suspended solids (VSS)*: connected to the amount of volatile substances found in the wastewater's solid portion
- *Chemical oxygen demand (COD*): amount of the dissolved oxygen needed to oxidize organic material. Typically, COD of the influent ranges between 0.3-1 g/L, and after treatment, it can be around 0.02 g/L [5,25,29].
- *Biological oxygen demand (BOD*): The oxygen required by bacteria to degrade organic matter Municipal wastewater might have an average BOD of 200–300 mg/L.
- *Carbon/nitrogen (C/N) ratio:* The ratio of carbon to nitrogen (C/N) is essential for the effective production of methane gas in WWTPs. While nitrogen is important for the growth and reproduction of anaerobic bacteria, carbon supplies the energy required for the creation of biogas. To reach the ideal range (about 20:1–30:1) for anaerobic digestion, carbon-rich feedstock must be added to sewage sludge, which often has a low C/N ratio (below 10:1). A low C/N ratio can cause too much nitrogen to be converted to ammonia, which will reduce the efficiency of digestion, while a high ratio can prevent the digestion process from starting.[42,12]

b. Design and operational parameters:

Each stage of anaerobic digestion requires specific optimal conditions to operate efficiently. Thus, it is crucial to consider these factors when designing the system and some of the key parameters are listed below:

- ***pH:*** While methanogens need a tighter pH range of 6.5 to 7.5, the ideal pH range for methane generation is 6.8 to 7.2. Acidogenic bacteria have a wider pH range of 4.5 to 8. It is crucial to monitor continuously and correct before being fed if it differs from required levels for balancing acid-producing and methane-producing bacteria since acid-producing bacteria, which multiply faster than methane-producing bacteria, can cause increased acid production and decreased methane production. [42,29,37,12].

- ***Alkalinity:*** The stability of the digester is improved by a high concentration of alkalinity. Low levels may result from the buildup of organic acids, the inability of methane-forming microorganisms, or the presence of substances that prevent the bacteria from doing their jobs [29,38].
- ***Temperature:*** It significantly influences the properties of organic material and the growth of bacteria during anaerobic digestion. The main operational temperature ranges are mesophilic (30-38°C) and thermophilic (50-57°C), with optimal temperatures for acidogenesis at 25-35°C and methanogenesis at 32-42°C. Most WWTPs prefer mesophilic conditions (35-37°C) due to easier control, adaptability to environmental changes, stability, and lower operational costs. However, thermophilic conditions (40-65°C) facilitate faster biochemical reactions, higher methane production rates, and more efficient destruction but require more heating energy and smaller reactor volumes [42,12]
- ***Retention time*:** Solid retention time (SRT) and hydraulic retention time (HRT) represent the average duration that bacteria and feedstock remain in the reactor. Typically it is around 20 days; longer times improve digestion but require larger digesters. Shorter HRTs can result in inadequate sludge stabilization, lower biogas production, and higher biosolid volumes [42,12]
- ***Organic load rate (OLR):*** It quantifies the amount of carbon in the digester feedstock during a given time period and is affected by temperature, digester type, digester flow, HRT, and volume. It influences biogas production, with an optimal OLR necessary for efficient anaerobic treatment. Higher OLR can enhance biogas production, but excessive OLR can lead to acid accumulation and reduced gas production. On the other hand, less organic feeding also results in less gas output. [42,12].
- ***Digestion volume:*** It is affected by OLR, pre-treatment process and sludge flow. [25]
- ***Digester mixing:*** Ensures uniform contact between bacteria and organic matter, enhancing fermentation efficiency. Impellers, pumps or gas recirculations are the methods can be used and they can increase gas production by 10-15%. [41,12]
- ***Digestion stages:*** There are one or two- stages of digestion which the process occurs. While two-stage offers higher performance, it has increased sensitivity and costs [42]

- ***Digester type:*** There are various types of digesters with different operational characteristics including the continuous stirred-tank reactor (CSTR), up-flow anaerobic sludge blanket (UASB), expanded granular sludge bed (EGSB), anaerobic baffled reactor (ABR), anaerobic fluidized bed reactor (AFBR) and the up-flow blanket filter (UBF) [42].

3. Inhibition: Toxic compounds such as ammonia, sulfide, heavy metals, and organic compounds can inhibit anaerobic digestion. Indicators of inhibition include increased volatile fatty acids, decreased pH, lower biogas and methane concentrations, and reduced microorganism populations. Low concentrations of heavy metals can enhance bacterial growth, but high concentrations and substances like soaps and disinfectants reduce methane production [42,12].

Increasing Biogas Production Inside WWTP

1. Biogas optimization strategies

a.Pretreatments for sewage sludge:

The objectives of sewage sludge pre-treatment are to boost biogas generation, decrease sludge volume and weight, speed up the anaerobic digestion process, and improve the sludge's biodegradability and solubility. This process releases intracellular materials by dissolving rigid structures and cell walls, producing simpler molecules that are easier for microbes to consume. Higher organic loading rates, shorter hydraulic retention times, faster solids reduction, higher methane concentrations, and higher-quality biosolids are all results of effective pre-treatment [42,73]. There are various methods in order to achieve these aims:

Mechanical: Its goal is to make particles more accessible to microorganisms by increasing their contact surface area. This procedure involves breaking up sludge cells and agglomerates with pressures like shear stress in order to increase the effectiveness of anaerobic digestion. High-pressure homogenizers, pulse methods, ultrasound and microwave are examples of common mechanical techniques; of these, ultrasound and microwave are the most researched and used. These approaches usually involve a moderate amount of power consumption and are frequently used in conjunction with other strategies to increase the overall efficacy of sewage sludge digestion [42,73].

Thermal: Uses heat typically between 60-200 °C and around 10 bars as a pressure in order to break down cell walls, solubilize compounds, accelerate hydrolysis, reduce HRT and enhance biogas production. Majority of the times thermal hydrolysis is used and can increase biogas production by up to 150% [42,39,76,12].

Biological: Reducing and eliminating organic matter and nutrients from wastewater is the primary goal of biological treatment in order to comply with regulatory limits and effluent disposal requirements. The most popular methods include temperature phase, enzyme addition, aerobic digestion, and dual-stage digestion. The goal of dual digestion is to physically divide the phases of methanogenesis and hydrolysis. The stabilization, biodegradability, and methane generation of the sludge are all enhanced by the addition of enzymes [42].

Chemical: Chemical treatments use reagents to hydrolyze organic compounds, enhancing hydrolysis rates and biogas production. The most widely used methods include oxidation processes, ozonation, and alkaline and acid hydrolysis. Because alkaline treatment is so effective at altering pH, increasing rates of hydrolysis, and solubilizing organic molecules, it is the most often employed chemical technique. While ozonation improved biodegradability, hydrolyze potential, and sludge mass reduction, acid hydrolysis and oxidation concentrated on improving hydrolysis performance and biogas output [42].
Pre-treatment is particularly beneficial for secondary sludge and can improve gas production by up to 30%, though it is energy-intensive and must be carefully evaluated [42,73]

b.Co-digestion
Co-digestion is an effective method for enhancing macronutrient balance, adjusting moisture levels and diluting toxic substances [16]. This technique, which is especially helpful when the feedstock has a low C/N ratio, entails combining sewage sludge with other organic feedstocks to increase biogas production and methane yield. Because most co-substrates produce methane at a rate significantly higher than sewage sludge per tonne of fresh materials, this could result in a large increase in gas output. In addition to increasing the production of biogas, co-digestion produces mechanical, thermal, or electrical power, which brings in extra income. Enough infrastructure must be in place for handling, storing, and pre-treating extra substrates for the deployment to be successful.

Adequate feedstock is required for sustainable codigestion, in accordance with the national regulation. Attractive co-substrates include fats, oils, and grease (FOG), food waste, agricultural residues, livestock manure, and biofuel by-products [73-42].

Many energy-neutral plants in developed countries utilize biogas recovery through co-digestion [16]. Comparing co-digestion to single-feedstock digestion, biogas production can increase by 25% to 400% [42]. For instance, biogas production can rise from digester volume of 0.9–1.1 m³/day/m³ to 2.5–4.0 m³/day/m³. [42, 33] Koch et al. reported that adding 10% food waste as a co-substrate in a WWTP more than doubled energy recovery. Additionally, co-digesting 7% fat with mixed sewage sludge resulted in a 17% increase in biogas output. Sarpong and Gude found that using FOG for co-digestion could boost energy production by 0.08 kWh/m³, while the total energy requirement for the studied plant was 0.32 kWh/m³. Wickham et al. observed up to a 191% increase in biogas production using carbonated soft drinks as a co-substrate. Similarly, adding 3% glycerol as a co-substrate led to an 81% increase in biogas production, and using grease trap water as a co-substrate increased biogas production by up to 209%. Numerous plants employing co-digestion have achieved 100% energy neutrality and even net positive energy, including Zurich Wedholzli WWTP in Switzerland (42 GWh/year), Point Loma WWTP in the US (193 GWh/year), Grevesmuhlen WWTP in Germany (193 GWh/year), and Sheboygan Regional WWTP in the US (32 GWh/year) [9]. Table 8 illustrates the potential increase in biogas production rates for various co-substrates [16].

Table 8: *Biogas production rate increase after using different co-substrates. [16]*

Co-substrate	Condition	Energy production without co-substrate (kWh/d)	Energy Production with co-substrate (kWh/d)	Biogas Production without co-substrate (L/gVS/day)	Biogas Production with co-substrate (L/gVS/day)
Microalgae	–	774	1189	–	–
Cheese whey	–	774	1531	–	–
The organic fraction of municipal solid waste (OFMSW)	Volumetric ratio 75:25; HRT 20 d	7688	8418	–	–
Dry waste (DW)	Volumetric ratio 80:20; HRT 16 d	677	10,639	–	–
OFMSW + DW	Volumetric ratio 68:23:9; HRT 18 d	6037	8972	–	–
Grease (G)	TS: G; 50:50	–	–	0.48	0.78
Septage (SP)	TS:SP; 90:10	–	–	0.48	0.46
Whey (W)	TS: W; 70:30	–	–	0.48	0.75

2.Biogas Utilization and Upgrading

a. Only heat production:

Biogas can be used to produce heat by combusting it in boilers, which's an straightforward and cost-effective method. The heat generated from biogas combustion can be used for various applications within the WWTP, such as maintaining the temperature of anaerobic digesters, heating buildings, and drying sludge. However, its effectiveness is limited to scenarios therefor it is generally not a preferred option [42,74].

b. Combined heat and power production:

CHP systems are known for their efficiency, in converting biogas into both electricity and heat making them particularly advantageous for WWTPs [74]. It is recommended to implement CHP technology in all biogas plants especially when utilizing generated heat within the plant or for external purposes [42]. According to an estimate made by USEPA the implementation of CHP systems in 544 US WWTPs with anaerobic digestion could lead to energy savings to the emissions from 430000 cars. An example of this application can be seen at the Psyttalia WWTP in Greece, where the use of CHP resulted in the lowest annual energy consumption amounting to 15 kWh/PE compared to ten other studied WWTPs [16].

CHP systems utilize a range of technologies such, as Otto engines, diesel engines, gas turbines, Stirling engines, Rankine cycles and fuel cells. These systems aim to maximize energy extraction from biogas by utilizing both the electricity generated and the thermal energy produced. In WWTPs the thermal output from CHP systems can be utilized for tasks like digester heating, space heating and other thermal processes within the facility and the electricity produced can be used onsite to power equipment and operations reducing reliance on power sources. To ensure performance and durability of CHP systems it is crucial to treat biogas to eliminate impurities like moisture, hydrogen sulfide, halogenated hydrocarbons and siloxanes. Incorporating waste heat recovery technologies such as the Organic Rankine Cycle (ORC) or absorption cooling systems can further boost energy recovery efficiency making CHP systems an highly efficient option for WWTPs [74].

c.Upgrading biogas to biomethane

The main objective of biogas upgrading is to eliminate impurities, producing biomethane with around 95-97% methane purity. This enhanced biomethane is suitable for use in CHP plants, injection into national gas transmission networks, or direct sale as a biofuel. Upgrading biogas not only enhances energy management but also complies with stringent regulatory standards for gas grid injection, which differ from one country to another [74]. Advancements in technology have shifted the trend towards upgrading biogas to biomethane instead of using it in CHP. Currently, 15 EU countries convert biogas to biomethane, with 10 injecting it into the gas grid. Germany, the UK, and Sweden lead in the number of biomethane plants [16].

Several European nations have established an infrastructure to facilitate the adoption of biomethane as a fuel for vehicles. This includes a network of refueling stations and a considerable number of biogas powered vehicles. For WWTPs, producing biomethane offers a clean fuel alternative and potential revenue from sales. Moreover, utilizing biomethane as vehicle fuel contributes to lowering GHG emissions and promotes supports sustainable management strategies [74,10,42,3].

Several technologies that take advantage of the various chemical and physical characteristics of gases have been developed for the upgrading of biogas such as pressurized water scrubbing (PWS), chemical absorption (CA), membrane separation (MS), organic physical scrubber (OPS), cryogenic separation (CS) and pressure swing adsorption (PSA). Every technology has a different mechanism: membrane system uses different permeabilities of CO_2 and CH_4 absorption depends on differences in gas solubility, cryogenic distillation uses gases boiling points, and PSA uses the selective affinity of CO_2 under different pressures[3,42]. These methods have their own pros and cons.For instance, while physical and chemical scrubbing methods are effective, they are energy-intensive. Pressure swing adsorption is less energy-intensive but more complex. Membrane separation technologies are environmentally friendly and consume relatively low energy, whereas cryogenic separation requires high energy for cooling [8]. The summary of these techniques is shown in the Table 9 The optimal upgrade method must be chosen after a through analysis that balances energy use and environmental effects, frequently with the aid of specialized modelling tools [3,42].

New technologies are being developed to reduce GHG emissions from biogas upgrading by focusing on using CO2 for methanation, which involves combining CO2 with hydrogen to generate methane. However, this process requires significant amount of initial and operational costs especially for producing hydrogen [8].

Nguyen et al. [9] found CHP effective in achieving a negative CF, while biogas upgrading to biomethane had a higher CF due to the energy-intensive process. Ravina and Genon concluded that CHP with thermal energy utilization produces the lowest CO_2 emissions (−0.277 tCO_2/t biogas). Biomethane upgrades to Italy's national grid (−0.13 tCO_2/t biogas) allow for cost-effective storage. Thus, biomethane upgrading may be more sustainable than CHP if gas energy is not fully utilized, aiming to reduce methane slip below 4%, with a target of 0.05% .

Table 9: Characteristics of biogas upgrading methods [42]

Method	**Energy Required (kWh/m³)**	**CH4 Recovery Rate (%)**	**Benefits**	**Drawbacks**
CA	0.06–0.17	99.9	-Produces the highest biomethane purity - No need for pressurized biogas - No need for H2S treatment	- Requires Prior H2S treatment - Needs heat, water, and chemicals -Higher energy consumption -Issues with corrosion and precipitation
CS	0.18–0.25	98–99.9	- No water and chemicals needed - High biomethane purity	- Requires biogas treatment - Needs prior H2S treatment - Not fully developed technology - High investment and operational cost
PSA	0.16–0.35	90–98.5	- No water and chemicals needed - Low energy consumption - Compact technology - Widely used in small-scale sites	- Lower biomethane purity compared with other methods - Requires prior H2S treatment - High energy consumption and strict process control
PWS	0.20–0.30	98–99.5	- Low energy consumption - Simple, flexible, and low operational costs - Remove NH3 and H2S - Most used type	- Requires drying process - More strict process control - Chemicals may be required - High water demand
OPS	0.23–0.33	96–99	- Remove NH3, H2S and other compounds - High biomethane purity	- High investment and operational costs - Higher energy consumption - May require heat and chemicals
MS	0.18–0.35	85–99	- Simple, flexible, and low operational costs - Compact and reliable technology - No chemicals, water, or heat required	- Require multiple stages - High investment costs (membranes) - Not fully developed technology - Can be inefficient - Not recommended for biogas with many impurities

Summary of literature studies about improved biogas production in WWTPs

Borzooei et al. (2020) studied ways to decrease the CF of the Italian largest WWTP by increasing biogas production and incorporating microalgae technology. They used a model-based feasibility analysis to assess the effectiveness of implementing a dynamic sludge thickener and hybrid thermo alkali pre-treatment resulting in an 18% rise in biogas production. By enhancing the biogas to biomethane with 98.6% efficiency through membranes they notably reduced energy usage and overall GHG emissions. The research also involved a lab-based feasibility analysis of microalgae technology using a designed planar photobioreactor achieving CO_2 reductions of 80% and 70% under varying intensities with CO_2 consumption rates of 11.763 and 27.943 mg/l/hour. These innovations led to a 41% drop in GHG emissions with specific emissions decreasing from -0.278 to -0.394 tons CO_2e, per ton of biogas produced. The generated biomethane replaced 63740 MWh/year of natural gas consumption [3].

Budych-Gorzna et al. investigated the enhancement of biogas production at a WWTP in Kozieglowy, Poland, through co-digestion with poultry industry waste. Their research involved both laboratory and full-scale trials to determine the optimal poultry waste dosage for co-digestion with primary sludge (PS) and waste-activated sludge (WAS). Laboratory trials showed that poultry waste produced between 0.39 and 0.88 m^3 CH_4 per kg of volatile solids (VS), while the production was 0.81 m^3/kg VS for the full-scale trials. Introducing poultry waste improved biogas production by 30%, significantly boosting the WWTP's energy self-sufficiency, potentially covering up to 80% of its energy requirements [41].

Lima et al. explored methods in order to increase biogas production from sewage sludge in WWTPs, with a focus on energy self-sufficiency. Their study delved into the techniques such as co-digestion, pre-treatment, optimization models, additives, and advanced techniques like Biological Hydrogen Methanation (BHM). They discovered that co-digestion with organic waste can rise biogas production by 20-30%, while thermal hydrolysis can increase yields around 50% and decrease sludge volume by 60%. By utilizing optimization models and chemical additives it is possible to further increase biogas yields by up to 20% and 10-15%, respectively. Implementing two-stage anaerobic digestion can enhance yields by 15-25%, and BHM has the potential toe generate 450 m^3/h of methane from CO_2 and hydrogen at an industrial scale. Although these advancements, challenges such as high costs, complexity, and the requirement for advanced optimization algorithms persists [42].

Hagos et al. reviewed the anaerobic co-digestion (AcoD) process for biogas production, highlighting its potential to boost its yields by 25% to 400% compared to mono-digestion. The study underscored how important to maintain optimal carbon-to-nitrogen (C/N) ratio of 20-30 for stability and efficiency. Advances in technology including the use of nanoparticles and additives were found to enhance yields and process stability. Moreover, the study pointed out the advantages of two-stage anaerobic digestion systems over the ones with single-stage. Nevertheless, challenges such as varying feedstock composition, changing conditions while transitioning from lab scale to industrial scale, and maintaining stability remain prevalent [67].

The research conducted by Özcan et al. examined how much biogas could be generated from wastewater treatment plants in areas of 16 cities, in Turkey. The study found that these plants could together produce about 1.88 billion kWh of energy per year from biogas. They calculated that each person generates 0.025 m^3 of biogas daily resulting in a production of 827565 m^3 for the combined population of these cities. With the value of biogas at 22.4 MJ/m^3, the yearly gas production is estimated to be around 302 million m^3 with an energy potential of 6.76 billion MJ, equivalent to about 1.88 billion kWh [68].

The study by Kaosol and Sohgrathok (2013) examines how to enhance biogas production through the anaerobic co-digestion of wastewater with decanter cake from the palm oil mill industry. The research evaluates the effects of different wastewater types, mixing conditions, and temperatures on biogas yield using batch digesters. The highest biogas yield was obtained by co-digesting decanter cake with rubber block wastewater, resulting in 3809 mL CH_4 /g COD removal and a maximum methane content of 66.7%. When combining seafood wastewater it produced between 58 to 422 milliliters of CH_4 /g COD, containing methane levels from 50.6%, to 66.7%. When co-digested with decanter cake rubber block wastewater outperformed seafood wastewater in terms of methane and biogas yields. The research revealed that neither mixing nor mesophilic temperature had an impact, on biogas generation suggesting that natural conditions are sufficient for optimal biogas output. Overall, co-digestion with decanter cake significantly improved biogas yields, its potential to improve waste treatment plants methane generation efficiency and waste management processes [69].

In their research conducted in 2024 Gupta and Khatiwada revealed that by combining biogas recovery from wastewater and sewage sludge it was possible to produce 137 GWh of energy leading to the avoidance of up to 38500 tons of CO_2 equivalent emissions each year. This approach proved to be financially viable showing a value (NPV) of 14.88 million € and savings worth 42.4 million € through avoiding natural gas usage amounting to 172.34 million m^3. The economic feasibility was influenced by factors such as wastewater quality, energy prices and capital expenses [70].

Masłoń conducted an examination how implementing sludge management techniques can optimize biogas production and decrease GHG emissions. The plant has a capacity of 25000 m^3/day. On average the facility produces 4290 m^3 of sewage sludge per month. Through digestion in two fermentation chambers and an open basin, the plant generates between 48789 to 74637 m^3 of biogas monthly containing 60-65% methane and having a calorific value ranging from 16.8 to 23 MJ/m^3. The daily average biogas production amounts to 2,080.9 Nm^3 and it is utilized for electricity and heat generation meeting 52.2% of the plant's energy requirements. The electricity output varies between 1.16 to 2.21 kWh/Nm^3, resulting in a total annual generation of 1.45 GWh. The research proposes that incorporating substrates such as waste fats, through co-digestion could further boost biogas yields and enhance energy efficiency [37].

Milani and Bidhendi (2023) conducted a study, on how combining biogas and solar energy in WWTPs can boost energy recovery and cut down on GHG emissions. They specifically looked at using an upflow anaerobic sludge blanket (UASB) reactor along with an activated sludge processing system (ASPS) reactor. The UASB reactor successfully generated 9120 m^3/day of biogas producing 6421 MWh annually and reducing CO_2 emissions by 3317 tons/year. Similarly, the ASPS reactor produced 14004 m^3/day of biogas generating 9860 MW·h yearly and lowering CO_2 emissions by 5092 tons annually. This combination of biogas and solar power has the potential to fulfil, up to 88% of WWTPs yearly energy needs while significantly cutting down on carbon emissions 10% to 40%. recommended further research into optimizing co-design of wastewater processes to maximize biogas energy recovery and the potential benefits of innovative PV technologies [38].

The study by Santos et al. (2016) explored the feasibility and potential decrease in CO_2 emissions by using biogas from a WWTP in Brazil to operate a power plant. This power plant was specifically designed to utilize biogas produced through treatment processes taking into account the increasing population. The study assessed three scenarios; selling electricity at two different tariffs and using the generated energy to fulfill the WWTPs energy needs. The results indicated that the project was financially feasible when the WWTP internally utilized the energy, showing a positive NPV and internal rate of return (IRR) exceeding 12%. The biogas-powered facility could meet over 59% of the WWTPs energy demands leading to a reduction of 0.79 tCO_2 annualy [39].

In a research study conducted by Abusoglu et al. in 2021, they delved into the utilization of biogas generated from WWTPs in Turkey for both district heating (DH) and electricity generation. The study presented two scenarios; Scenario I involves utilizing surplus biogas storage and exhaust gas from cogeneration while Scenario II focuses on using all the biogas produced for cogeneration purposes. In Scenario I the waste heat from cogeneration is capable of heating 458 households however with purified biogas it is possible to meet the natural gas requirements of 1112 homes. On the hand Scenario II is able to produce 1643 kWh of electricity and provide heating for 755 households. The payback periods for these scenarios are estimated at 2.5 years for Scenario I and 2 years for Scenario II [40].

The research conducted by Masloń et al. offers an examination of enhancing energy efficiency in a WWTP processing around 6176 m^3 of wastewater daily serving around 32500 residents. Through the co-digestion of sewage sludge and poultry waste the WWTP generates an average of 3063 m^3/d of biogas with biogas yields ranging from 18.3 to 32.2 m^3 /m^3 co-substrate, significantly improving the plant's energy efficiency by meeting 93.0% to 99.8% of its energy requirements. The study emphasizes the benefits of co-digestion over mono-digestion processes in terms of enhancing biogas production and process efficiency. While mono digestion resulted in a methane yield of 0.3 m^3/kgVS co digestion with poultry waste increased the yield to 0.547 m^3/kgVS with enhancement rate of 82%. Furthermore, incorporating co-digestion improved VS and organic compound removal efficiency.

The biogas produced is used for both electricity generation and heat production. The plant's co- generators produce 0.696 MW of electricity and 0.881 MW of thermal energy. The extra thermal energy is utilized for heating needs, within the plant like regulating digester. In general, the research indicates that integrating co-substrates such as poultry waste can notably improve biogas production and energy efficiency in WWTPs [56].

2.2. REDUCTION OF GHG EMISSION IN WWTPS

WWTPs are widely recognized for their contribution to GHG emissions and there is a rising concern because of their significant impact. Despite their ability to maintain water quality under unpredictable conditions such as heavy rainfall the associated high costs and substantial CO_2 emissions have become a pressing issue. Typically, assessments of impacts often focus only on point source discharges overlooking broader effects. The increasing need for cost protection and the growing worries about GHG emissions are prompting efforts toward more sustainable WWTP operations. Various strategies have been explored to address these emission concerns. This section will delve into mitigation approaches that can effectively reduce GHG emissions in WWTPs (Figure 16) [30].

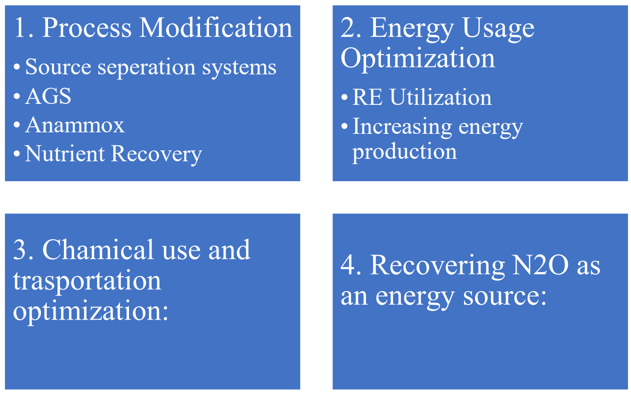

Figure 16: GHG mitigation from the WWTPs

2.2.1. Mitigation of GHG emissions via process modification

Although current wastewater treatment processes emit substantial amounts of GHGs, new research indicates that, with appropriate modifications, biological methods can offer cost-effective and eco-friendly solutions for mitigating GHG emissions in WWTPs.

2.2.1.1. Source separation systems

In these systems, grey water (GW), black water (BW) and food waste (FW) are segregated from wastewater and solid waste, as illustrated in Figure 17.

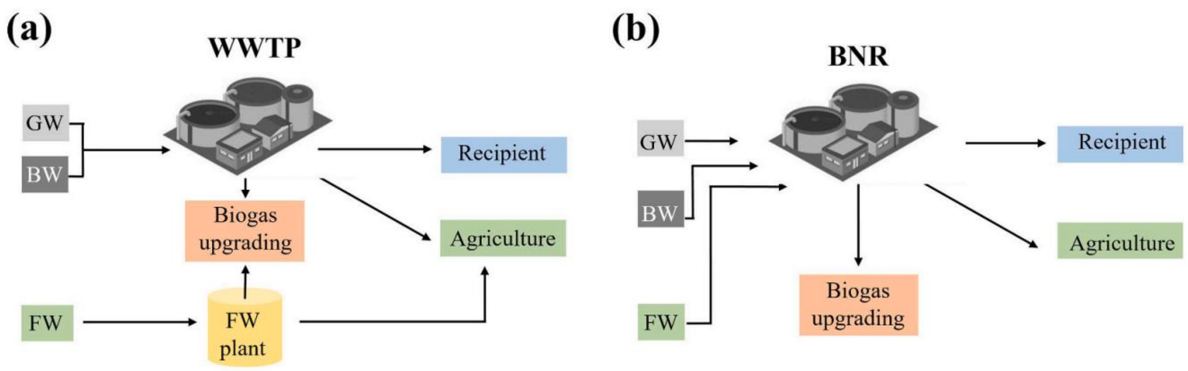

Figure 17: a. Conventional systems vs b. source separation system of wastewater treatment [16].

Separating different types of wastewater at the source can greatly enhance the efficiency of treatment, recovery, and biogas generation. According to Kjerstadius et al. implementing a source separation system in WWTPs resulted in a reduction of 34 kg CO_2e/PE annually mainly due to an increase in biogas production. Similar outcomes were reported by Remy. On the contrary, Thibodeau noted a CF associated with source separation mainly because of transportation emissions; however, this could potentially be offset by selling bio products as fertilizer.

Source separation also improves the recycling of nutrients, in areas resulting in returns of nitrogen and phosphorus. According to Besson et al. [16] segregating urine and black water maximizes retrieval, and cuts down GHG emissions by 60% thereby avoiding emissions linked to nitrogen fertilizer manufacturing.

Tian et al. [5] demonstrated that using urine wastewater to pretreat waste-activated sludge (WAS) before AD led to a 23% increase in methane production. The combination of hydrolyzed ammonia present in urine wastewater effectively enhanced sludge decomposition, resulting in a decrease in sludge volume and an increase in the availability of substrates for biological treatment processes. Badeti et al. [72] found that urine diversion could save 33% of aeration energy and significantly reduce direct N_2O and CO_2 emissions in WWTPs. In the case study from Hiedanranta, Finland, Lehtoranta it is observed that source separation recovered nitrogen while reducing environmental impacts compared to conventional systems.

2.2.1.2. Aerobic granular sludge (AGS*)*

In AGS systems, both aerobic and anoxic zones exist, where anoxic denitrification may act to lower N_2O emissions and create around 7% reduction in indirect GHG emission. Nevertheless, various studies have reported a broad range of N_2O emission factors (0.33-22%) for AGS under different operational settings, creating uncertainty about whether AGS consistently produces less N_2O than conventional activated sludge (CAS) [76].

In comparison to conventional activated sludge (CAS), this method offers more than double microbial concentration, higher biochemical reaction rates, improved effluent quality, reduced land usage, and lower requirements for chemicals and energy. The largest AGS wastewater treatment facility in China, processing 80000 m^3/day, can save up to 1.46 million kWh annually in electricity and cut carbon emissions by 882 tons per year compared to CAS. Another plant in China, implemented AGS technology to significantly increase its capacity by more than threefold, resulting in over a 20% reduction in both energy consumption and chemical usage [76].

2.2.1.3.Anaerobic ammonia oxidation (Anammox)

The Anammox process, an autotrophic method for biological nitrogen removal (BNR), utilizes nitrite as an electron acceptor to oxidize ammonium into nitrogen under anaerobic conditions. This approach is more cost-effective and sustainable for eliminating reactive nitrogen from wastewater compared to CAS method. The Anammox process can reduce carbon emissions by over 50% due to its lower oxygen demand (63% less) and elimination of external carbon sources, theoretically resulting in zero N_2O emissions. This makes it highly beneficial for achieving "energy-neutral" or even "energy-positive" wastewater treatment in urban areas. Beijing's Anammox denitrification project, which has the largest sludge digestion capacity globally at 15900 m^3/day, is expected to reduce annual carbon emissions by approximately 10500 tons of CO_2-equivalent. However, due to the need for nitrite and the low-oxygen environment, Anammox is typically used alongside nitrifiers and heterotrophic denitrifiers, which can produce N_2O during the BNR process. Some studies have found that partial nitritation/anammox systems have higher N_2O emissions than CAS. Nonetheless, N_2O emissions can be significantly reduced by using Anammox technology with low N_2O^- generating nitrifiers, such as ammonia-oxidizing archaea [16].

N_2O production in anammox-based systems occurs through three primary pathways. The first involves NH_2OH oxidation, where ammonium (NH_4+) is converted to hydroxylamine (NH_2OH) and then to N_2O(($NH4$ + $\rightarrow NH_2OH \rightarrow N_2O$). The second pathway is autotrophic denitrification mediated by ammonia-oxidizing bacteria (AOB), where nitrite (NO_2-) is converted to nitric oxide (NO) and then to N_2O, or NH_2OH is directly converted to N_2O, or through the reaction of NH_2OH with NO to produce N_2O ($NO_2 \rightarrow NO \rightarrow N_2O$ or $NH_2OH \rightarrow N_2O$ or $NH_2OH + NO \rightarrow N_2O$). The third pathway is heterotrophic denitrification, where nitrate (NO_3-) is sequentially reduced to nitrite (NO_2-), then to NO, and finally to N_2O by various denitrifiers($NO_3 \rightarrow NO2 \rightarrow NO \rightarrow N_2O$).

These systems are categorized into four types: partial nitritation anammox (PN/A), simultaneous PN/A and denitrification (SNAD), partial denitrification-anammox (PD/A), and denitrifying anaerobic methane oxidation (DAMO)-anammox (DAMO/A) (Figure 18). PN/A and SNAD efficiently treat wastewater high in ammonia, while also lowering energy usage and sludge production compared to conventional nitrification-denitrification processes. Conversely, PD/A and DAMO/A are suited for nitrate-rich wastewater, emphasizing reduced energy consumption (no oxygen required and C/N ratio under 3) and achieving effective removal rates. As a result, anammox-based systems are becoming a promising solution for energy-neutral operations in WWTPs [16].

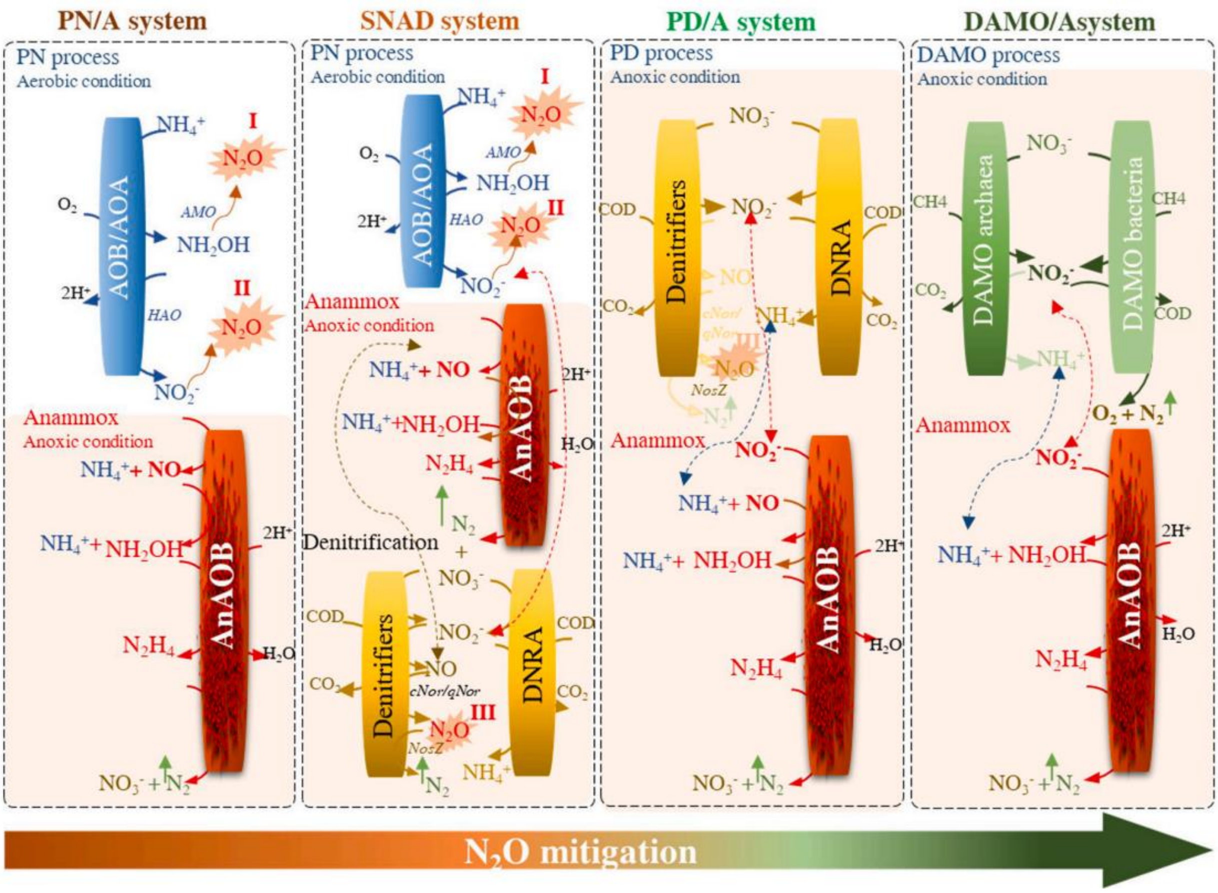

Figure 18: Anammox based N removal systems [16]

PN/A. N_2O emissions in partial nitritation anammox (PN/A) systems range from 0.08% to 6.6% of the nitrogen load. These emissions can be reduced by adjusting the NO_2-/NH_4+ ratio, C/N ratio, aeration strategies, DO levels, temperature, and pH. Low DO levels lead to NH_2OH oxidation as the main N_2O source, while higher inorganic carbon, lower pH, or increased NO_2- concentrations enhance AOB denitrification. Intermittent aeration can shift these pathways, reducing emissions. Beier et al. found an N_2O emission factor of 0.05 mg N_2O/mg NH_4+ during aeration and 33% during anoxic phases, mainly from denitrification. High NO_2-/NH_4+ ratios increase N2O production, whereas lower NO_2^- and higher NH_4^+ loads reduce it.

SNAD. N_2O forms through the oxidation of NH_2OH by ammonia-oxidizing bacteria (AOB) and the reduction of NO_2- to NO and then to N_2O under aerobic conditions, as well as through heterotrophic denitrification in anoxic conditions. In SNAD systems, N_2O emissions are about 4% lower than in PN/A systems due to decreased NO_2^- levels, which are utilized during anammox metabolism. Using the NosZ enzyme for full heterotrophic denitrification has proven effective in reducing N_2O emissions, with SNAD biofilters cutting N_2O emissions by 80% and 70% compared to conventional nitrification and nitrification-denitrification biofilters.

PD/A: In partial denitrification/anammox (PD/A) systems, microorganisms such as AnAOB and heterotrophic DNRA bacteria compete for nitrite (NO_2^-), playing a key role in reducing N_2O emissions. N_2O is not produced during the anammox process or partial denitrification. These systems show low N_2O emissions both with and without the addition of COD, achieving up to a 50% reduction in N_2O emissions when COD is added due to the activity of the NosZ enzyme.The main challenge is maintaining a balance of NO_2^- through the activities of denitrifiers and AnAOB. Proper COD addition is crucial for mitigating N_2O emissions. Further research is required to better understand PD/A microbial metabolism and growth rates to improve nitrogen and COD removal efficiencies in WWTPs.

DAMO: DAMO microorganisms include DAMO archaea and bacteria. DAMO archaea reduce NO_3^- to NO_2^- using CH_4 under anoxic conditions, mitigating N2O and CH_4 . DAMO bacteria complete denitrification (NO_3^- to N_2) using CH_4 as an electron donor. Combining DAMO microorganisms with AnAOB offers several benefits: CH_4 reduction in effluent to 15%, minimal N_2O emissions, 99% nitrogen removal efficiency, and 49% cost savings. DAMO/A systems emit negligible N_2O due to the absence of N_2O^-generating enzymes in DAMO archaea and AnAOB, and DAMO bacteria efficiently remove excess NO_2^- . These systems are gaining attention as sustainable alternatives to traditional nitrification-denitrification in WWTPs. However, high NO_3^- levels can hinder N_2O reduction by NosZ enzymes, leading to increased N_2O emissions. Further research is needed to fully understand DAMO/A microbial metabolism [16].

2.2.1.4. Systems with nutrient recovery

2.2.1.4.1. P recovery from wastewater

Urban wastewater has the potential to replace up to 50% of the mineral phosphorus (P) fertilizers used in agriculture, but mining P from phosphate rock leads to pollution of air and water. Amann et al. conducted a LCA of 18 P recovery methods and found that GHG emissions varied widely. Recovering P from the liquid phase was effective in reducing net GHG emissions, while recovery from sludge showed higher emissions. Recovery from sewage sludge ash proved to be the most efficient, reducing annual energy demand and GWP by 0.096% and 0.1% per PE, respectively. Duan et al. compared various P removal and recovery techniques, finding that chemical P removal had a CF of 44.5 kg CO_2e/kg P removed, whereas P recovery showed a CF of −3.76 kg CO_2e/kg P, indicating potential CF savings. Zhao et al. examined the A-2B-centered process in WWTPs, which captures chemical oxygen demand (COD) and recovers P with lower energy use and GHG emissions. Efficient P management in WWTPs involves balancing environmental protection, energy efficiency, and GHG emissions, with methods like the A-2B-centered process being particularly effective [16].

2.2.1.4.2. N recovery from wastewater

Recovering nitrogen (N) as a nutrient can significantly reduce both environmental impacts and energy use. Conventional nitrification-denitrification processes are energy-intensive and offer no additional benefits beyond regulatory compliance. In contrast, N recovery methods can treat wastewater more efficiently while reclaiming valuable resources. Beckinghausen et al. conducted an extensive review of about 50 N recovery techniques, particularly those capable of producing fertilizers. Permeable membranes emerged as a standout technique, requiring only 1–1.2 kWh per kilogram of N, and effectively recovering ammonium (NH_4^+) from wastewater to create ammonium sulfate, a marketable product. Another method, vacuum membrane distillation, can recover large amounts of energy as heat (27 kWh /kg N), but the process itself is very energy-intensive (60 kWh/kgN). Cutting-edge technologies such as membranes, sorbents, electrodialysis, bioelectrochemical processes, and even microalgae are being developed to improve nutrient recovery from wastewater, moving beyond traditional crystallization methods. Additionally, at full scale, certain physicochemical methods like air stripping and struvite formation are employed to recover phosphorus (P) and N from side streams [16].

2.2.2. Energy usage optimization

Energy consumption, which constitutes about 73.4% of total indirect GHG emissions, is primarily used for aeration, pumping, and heating. Enhancing the management of these areas through smart systems can significantly reduce GHG emissions. Since the specifics of these systems are covered in the Energy Optimization section, their impact on reducing GHG emissions will be briefly discussed [76].

One such technology is intelligent aeration, which can reduce energy use by 20-40% [58]. Additionally, it significantly mitigates N_2O emissions, achieving a 35-90% reduction in lab and full-scale BNR systems through strategies like lowering DO set points, decreasing aeration rates, and adjusting aeration schemes [16].

Decarbonizing the energy sector can reduce indirect emissions in WWTPs. Countries are replacing coal-fired electricity with natural gas and renewable resources like wind, solar, hydropower, and nuclear power and EF of them can be seen from Table 10.

Table 10*: EF calues for different sources of electric energy* [16]

Energy Source	**min (g CO_2e/kWh)**	**max (g CO_2e/kWh)**
Coal	675	1689
Oil	510	1170
Natural gas	290	930
Biogas	50	700
Hydropower	3	40
Nuclear power	4	110

Currently, fossil fuels satisfy about 88% of grid energy. Increasing renewable energy use by 25% over the next 20 years could lower the CF of the energy mix by up to 42%. Delre et al. found that in Danish WWTPs, reliant on fossil fuels, energy use contributed to 29% of the CF, while in Swedish WWTPs, using mostly nuclear and hydropower, it was as low as 3%.

One effective way to offset GHG emissions at WWTPs is by utilizing renewable energy, such as waste heat from wastewater using wastewater source heat pump (WWSHP) technology. WWSHP systems are widely used in China, though their efficiency is limited to a range of 3-5 km due to heat transfer constraints. A case study in Shenyang province showed that WWSHP for winter heating significantly reduced coal consumption and emissions: 71000 tons of SO_2, 727533 tons of soot, and 140000 tons of CO_2 annually. In Beijing, 17 reclaimed water plants using WWSHP from 2016 to 2020 achieved a heating capacity of 5.3 million GJ, saving 160 million m3 of natural gas. This technology can help WWTPs reduce CO2 emissions, contributing to carbon-neutral operations [76].

Photovoltaic (PV) power generation, which converts solar energy into electricity, can reduce GHG emissions from WWTPs [68]. By the end of the 13th Five-Year Plan which is referred in the energy optimization topic it is expected to increase by 17 MW by 2025, generating 18 million kWh annually and reducing CO2 emissions by up to 11,000 tons per year[76].

Another example is CHP technology using biogas and generate renewable electricity and heat, either for onsite use or export to the grid. This technology has been implemented in several projects, demonstrating significant carbon reduction. Although achieving "carbon neutralization" is challenging for WWTPs especially the ones with low organic loads, biogas energy recovery can offset more than half of energy consumption and reduce indirect CO_2 emissions by at least 50% [76].

The promotion of renewable energy, including thermal, solar, and biogas, is supported by strategies such as the Development Plan 2035 for Urban Water Sector [75,76]. These strategies are more applicable to large-scale WWTPs and are expected to reduce indirect GHG emissions by 10%, 3%, and 4% through the utilization of thermal, solar, and biogas energy, respectively [76].

2.2.3. Chemical usage and transportation optimization

Ambiguous GHG emissions from WWTPs are primarily related to chemical agent usage and transportation of by-products (grit, screenings, and sludge) [28].

2.2.3.1. Reducing chemical consumption

Chemicals are integral to various stages of wastewater treatment/sludge management and they cause 4.8% of indirect GHG emission from WWTPs [76,55]**.** In order to reduce their CF, both consumption cuts and sustainable purchasing criteria can be effective. According to the Ecoinvent database 3.6, upstream indirect emissions are 1964 kg CO_2e/kg for inorganic agents and 1909 kg CO_2e/kg for organic agents. Inorganic agents, such as aluminum sulfate, iron chloride, and lime, support enhanced biological phosphorus removal but increase sludge volume and pH, necessitating further chemical adjustments and raising GHG emissions. Using recycled inorganic agents can mitigate emissions from raw material extraction and production. Organic agents and polymers are used for flocculation, coagulation, and dewatering. Opting for bio-based polymers over synthetic ones can also reduce indirect GHG emissions. Chemical use affects the entire treatment process; for instance, chemicals in primary sedimentation boost biogas and energy production, while those in dewatering may be targeted for CF reductions through overall consumption cuts [16].

In addition, overdosing chemicals to meet nutrient removal requirements increases costs and emissions however, intelligent dosing technologies can mitigate these impacts. For example, the Changzhi WWTP reduced carbon source use by over 50%, and the Linyi Qinlonghe Plant cut carbon and phosphorus dosing by 13% and 27%, respectively, using intelligent systems [76].

2.2.3.2. Reducing transport-related CF

Transport activities, such as moving chemical agents and wastewater treatment by-products, contribute to the indirect emissions of WWTPs. Implementing transport-related emission reduction plans, like using rail transport or reducing distances, is often challenging. Therefore, advanced strategies are needed. According to DEFRA (Department for Environment, Food and Rural Affairs), GHG emissions depend on engine type, vehicle size, and load and emissions can be reduced by optimizing them as well as changing fuel type. Biofuels, particularly bioethanol and biodiesel, have been promoted to replace gasoline and diesel, offering at least 65% GHG savings compared to conventional fuels, as encouraged by the Renewable Energy Directive I and II [16].

2.2.4. Recovering N2O from wastewater as an energy source

Using N_2O as a source of energy can help produce energy while also reducing emissions. However, limited studies exist on N_2O recovery, which can be used as a powerful oxidant. Wu et al. introduced the Coupled Aerobic-Anoxic Nitrous Decomposition Operation (CANDO) process involving steps like:

-partial nitrification of NH_4^+ to NO_2^-,
-partial reduction NO_2^- to N_2O anaerobically,
-transforming N_2O to N_2 with energy recovery via catalytic decomposition or co-combustion with CH_4 .

Yu et al.described a novel method for recovering N_2O by inhibiting nitrous-oxide reductase in denitrifying bacteria and they achieved around 70% N_2O recovery in their experiments.

While CANDO is the most researched method for N_2O recovery, it requires further testing for consistent long-term performance. Other potential methods, such as autotrophic photoelectrotrophic denitrification, sulfur-driven denitrification, and hydrogenotrophic denitrification, are still in the early development stages [188]. High-strength wastewater offers greater energy and economic benefits for N2O recovery compared to low-strength wastewater and for this reason it is more favourable. Recent models by Deng et al. and Huo et al. show efficient N_2O recovery from Fe(II)EDTA-NO, with efficiencies up to 85%. Duan et al. identified key challenges, including unstable nitritation, limited energy potential, and risks from N_2O emissions in treatments [16].

3.METHODOLOGY

This part explains how the energy usage and GHG emissions were computed for the hypothetical WWTP baseline and two other scenarios; Enhanced Aeration System and Improved Biogas System. The computations rely on factors, energy consumption figures and specific assumptions provided in the following sections.

3.1. Summary of Calculations

The methodology includes aspects of evaluation to thoroughly assess different wastewater treatment scenarios. To begin with, initial values, for key wastewater parameters such as water consumption per person, BOD, COD, removal efficiency of them, DO are determined. These values lay the groundwork for understanding the conditions of the wastewater treatment process and calculating the mass and energy balances which're crucial for determining the energy consumption needed for processes such as aeration. Following this, biogas production is estimated by calculating the methane generated taking into consideration factors like biogas yield, COD transformed into biogas and methane loss. This process involves assessing the energy potential of the captured methane to comprehend energy recovery and utilization within the treatment process. Both direct and indirect emissions of CH_4 and N_2O are computed to present a view of impact and converted into CO_2 equivalents to measure their contribution to global warming. Lastly, scenario analysis examines enhancements in aeration system and biogas production efficiency. This analysis delves into how these enhancements can decrease energy consumption and GHG emissions while emphasizing the advantages of progress in wastewater treatment procedures.

3.1.1.Baseline Scenario

The baseline scenario involves comprehensive wastewater treatment processes for the treatment plant serving 800000 PE. Initially, primary treatment includes screening, grit removal, and primary sedimentation to remove large particles and settleable solids. The next step involves using an activated sludge method followed by sedimentation to reduce organic matter. To remove nitrogen, nitrification and denitrification processes are utilized, while phosphorus removal biological uptake and chemical precipitation. Sludge treatment incorporates anaerobic digestion AD for biogas production, thickening, and dewatering. Energy recovery is facilitated by a CHP system, which operates at 40% electrical efficiency and 35% thermal efficiency.

3.1.1.1. Wastewater Parameters-Mass Balance

Since the plant is assumed to be in Italy The average water consumption is taken as 0.25 m^3/person.day by using the data from Statista [97]. BOD is assumed to be 60 g/PE/day based on Table 6.4 for Italy from IPCC 2006 [27].

The following parameters and their calculations are critical for determining the overall mass and energy balances within the WWTP.

Nitrogen (N) Removal:

Nitrogen influent (Ninfluent) is assumed 8 g N/PE/d by using the sources for Italy [11,77] and since nitrogen removal efficiency (Nremoval) is assumed 75% [62],nitrogen effluent is calculated as 2 g N/PE/d.

N concentration in the digested sludge (N_{ds}) is calculated by assumptions made including N $f_{raction}$ 0.06 gN/gCOD by using data from literature [62] and obtained as 1.38 g N/PE/d. Then, by substructing, the sum of this value with $N_{effluent}$, from $N_{influent}$ nitrogen denitrified is calculated and obtained as 4.62 g N/PE/d. By using these values and below formulas, it is important to determine the Oxygen Uptake Demand for nitrogen (OUDN), and Oxygen Uptake Demand for Ammonium (OUNH4).

$$OUDN = N_{dn} \times 1.7$$

$$OU_{NH4} = (N_{influent} - N_{dn} - N_{ds}) \times 4.3$$

This gives an OUDN of 7.854 g O_2/PE/d and OUNH4 of 8.6 g O_2/PE/d and they will be used for calculating the energy requirement of the aeration system.

Phosphorus (P) Removal:

Phosphorus influent (Pinfluent) is assumed 1 g P/PE/d by using the sources for Italy [11,77] and since phosphorus removal efficiency (Premoval) is assumed as 85% [62] phosphorus effluent is calculated as 0.15 g P/PE/d.

COD Balance:

Influent COD ($COD_{influent}$) concentration is assumed as 95 g COD/PE.d [11,77] and the primary treatment (PT) stage P removal efficiency as 30% [62]. COD concentration removed during PT and residual COD concentration after primary treatment which is considered as the amount of COD entering the biological treatment stage ($COD_{influentBT}$) are calculated as follows:

$$COD_{PS} = COD_{influent} \times COD_{removal\ PT}$$

$$COD_{effluent\ PT} = COD_{influent} \times (1 - COD_{removalPT})$$

With the values substituted, COD content in primary sludge (COD_{PS}) and COD effluent ($COD_{effluentPT}$) are obtained as 28.5 and 66.5 g COD/PE/d respectively.

In the subsequent stages of the WWTP, it is assumed that 95% [11,62] of the influent COD is removed and COD concentration in the final effluent from the WWTP is calculated by using below formula and calculated as 4.75 g COD/PE/d.

$$COD_{effluent} = COD_{influent} \times (1 - COD_{removal})$$

The amount of COD respired by micro-organisms (COD-OUC) is calculated by using below formula:

$$CODOUC = (COD_{influentBT} - COD_{effluent}) \times (OUC/nCOD)$$

All other values are obtained up to this step to calculate COD-OUC except the OUC/nCOD ratio. This ratio shows the oxygen consumption required for the biological treatment process relative to the amount of COD present in the wastewater. It can be obtained by using below Table 11 which sludge age is determined as 13 and OUC/nCOD is 0.626. Substituting the values it is obtained as 38.655 gCOD/PE/d.

Table 11: Treatment Performance Based on Sludge Age and PE [62]

Sludge Age (d)	OUC Biological Stage	OUC/nCOD (Biological Treatment)
> 100,000 PE + AD, Primary Treatment 30%		
4	COD removal only	0.52
9	COD and NH4 removal	0.59
13	COD and N removal	0.626
15	COD and N removal by upgrading N removal from 75% to 85	0.643
30,000 ≤ PE < 100,000 + AD, Primary Treatment 30%		
4	COD removal only	0.52
12	COD and NH4 removal	0.61
16	COD and N removal	0.65
19	COD and N removal by upgrading N removal from 75% to 85	0.67
2,000 ≤ PE < 30,000 + Post-ASS - RB (No Primary Treatment)		
4	COD removal only	0.45
8	COD and NH4 removal	0.57
18	COD and N removal	0.61

Then, COD remaining in the excess sludge after the biological treatment process (COD_{ES}) is calculated by using mass balance in the biological treatment shown below formula and obtained as 23.095 gCOD/PE/d.

$$COD_{ES} = COD_{influentBT} - COD_{effluent} - CODOUC$$

3.1.1.2. Energy Balance and Biogas Production

a. Energy requirement of the Plant

The energy needed by WWTPs may vary depending on the facility's size, location, population served, the type of treatment methods it has, and required effluent quality [38,55] and there are plenty of studies analyzing the energy requirement of the plant and 2 of which are showed below. After overview, 0.47 kWh/m^3 is considered as reasonable value and this results in an overall energy requirement of 42.887 kWh/PE/y. Distribution of this total energy requirement as electrical and thermal energy requirement is determined through case studies of WWTPs in Italy and obtained 23.393 kWh/PE/y and 19.494 kWh/PE/y.

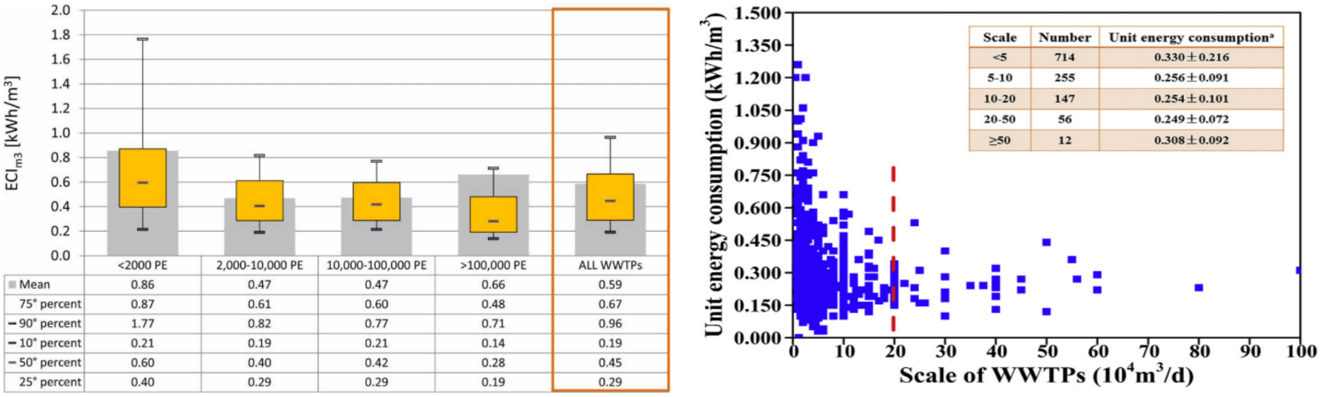

Figure 19: Some results of WWTP energy requirement analysis [6,55]

Requirement for aeration system

The below formula is used to calculate the energy requirement of the aeration system.

$$E_{aeration} = \frac{(CODOUC + OU_{NH4} + OU_{DN})}{(\propto SAE)} \times \frac{DO_{sat}}{DO_{tank}} \times \frac{365}{1000}$$

While CODOUC, OUNH4 and OUDN are calculated in the 'Water Parameters-Mass Balance' section, other variables are assumed by using the values from literature. Here αSAE (Oxygen Transfer Efficiency) is assumed as 1.98 kgO2/kW.h, based on typical conditions in WWTPs. Dissolved oxygen saturation (DO_{sat}) is assumed to be 10.2 mg/L, which corresponds to water at a temperature of 15°C under typical atmospheric conditions. After implementing all variables, electricity requirement of the aeration system is calculated as 12.636 kWh/PE/y.

b. Biogas and Energy Production

In order to calculate biogas production, biogas yield is used 0.35 L CH_4 /g COD removed [82] where it is necessary to estimate the amount of COD converted to biogas in AD. This is done by using below mass balance:

$$COD_{biogas} = COD_{RS} - COS_{DS}$$

Here are the explanation of the variables:
COD in Raw Sludge **(**COD_{RS})**:** The total COD present in the raw sludge, combining primary sludge and excess sludge, is 51.59 g COD/PE/d.

COD in Digested Sludge **(**COD_{DS})**:** After anaerobic digestion, the COD in the digested sludge is assumed as 23 g COD/PE/d by proportioning the COD influent and COD digested sludge ratio found in the literature [62].

In this case, the COD converted to biogas is 28.594 g COD/PE/d which will result in 10.01 L CH_4 /PE/d. However, there will be some methane losses during the process which the fraction is accepted as 3% [62] and this gives a methane production of 9.71 L CH_4 /PE/d. And as it is assumed that biogas is composed of 65% methane [38,40,41,42], daily biogas production is calculated as 14.94 L biogas/PE.

By using the calorific value of methane which is (10 kWh/m^3) [84] the maximum energy production in CHP system is calculated by multiplying the methane production (adjusted for losses) by the calorific value of methane (10 kWh/m^3) and converting it to an annual value. This results in a maximum energy production from methane of 35.43 kWh/PE/y. By considering electrical efficiency of the system as 40% and thermal system as 35%, electrical and thermal energy production is obtained as 14.17 kWh/PE/ and 9.22 kWh/PE/y, respectively.

Avoided Emissions

The avoided pollutant load from energetic recovery by using CHP system is calculated based on the emission factors of electricity and thermal energy which are 0.386 kgCO_2e/kWh and 0.404 kgCO_2e/kWh, [57] respectively. Using these emission factors along with their energy outputs avoided pollutants by producing electricity is calculated as 5.475 kg CO_2 eq/y and by producing thermal energy is 5.014 kg CO_2 eq/y. Finally, by summing them the total amount of avoided pollutants from energetic recovery is calculated as 10.489 kg CO_2 eq/y.

3.1.1.3.GHG Emissions

3.1.1.3.1. Methane Emissions

It is critical to consider CH_4 emissions from WWTPs when assessing the environmental impact of them. In this study, methane emissions are evaluated under two titles which are direct and indirect emissions that cover various stages of the hypothetical wastewater treatment process and post-treatment handling of sludge.

a.Direct Emissions

There are some key processes that cause CH_4 emissions which are calculated as below:

a. From water line

It is calculated as 0.326 g CH_4 /PE/d by using below formula with the EF of 0.0075 g CH4 /g COD [27].

$$Methane\ emission = EF \times (COD_{influent} - COD_{sludge})$$

b.Methane Emission from Sludge Reed Bed:

With an emission factor of 0.0025 g CH_4 /g COD sludge, [79, 85, 80] the methane emission from sludge reed bed is 0.129 g CH_4 /PE/d

c. CHP Slip, Leakages, and Dissolved Methane:

The combined emissions from CHP slip, leakages, and dissolved methane amount to 0.138 g CH_4 /PE/d by using below formula:

$$Methane\ emission = Methane\ production \times (EF_{slip} + EF_{leakage} + EF_{dissolved})$$

Here emission factor for methane slip (EF_{slip}), emission factor for methane leakage ($EF_{leakage}$) ; Emission factor for dissolved methane ($EF_{dissolved}$) are 0.015, 0.001 and 0.005, respectively [62,86,88].

***d.** Anaerobic Sludge Stabilization*:

Methane emission from this stage is 0.096 g CH_4 /PE/day when considering the emission factor for anaerobic stabilization is 0.015 sourced from [81,83,86].

e.Methane Emission from Anaerobic Sludge Storage:

The methane emission from anaerobic sludge storage is 0.34 g CH_4 /PE/d, considering further degradation of COD load in the storage tank [62,81,83,86].

b. Indirect Emissions

Indirect emissions from CH_4 considers receiving water bodies. COD of effluent is 6 g COD/PE/ as it was discussed under the title of mass balance and EF of receiving water body is 0.028 kg CH_4 /kg CODeff [27]. Therefore, emission from receiving water is calculated as 0.133 gCH_4 /PE/d.

c. Total Methane Emission

The summary of the calculation about methane emission can be seen in Table 12 and the total methane emission is the sum of all these individual methane emissions:

Table 12: Daily CH_4 Emissions

DIRECT EMISSION	
Methane Emission Source	**Emission Amount (gCH_4 /PE/d)**
From water line	0.326
From sludge reed bed	0.129
CHP slip, leakage and dissolved methane	0.138
Anaerobic sludge stabilization	0.096
Anaerobic sludge storage	0.34
INDIRECT EMISSION	
From receiving water bodies	0.133
Total	1.161

Total daily CH_4 emission is calculated as 1.161 g/PE which corresponds to 423 g/PE annually. And by using GWP factor from Table 3 yearly CO_2e is found as 11.868 kg/PE.

3.1.1.3.2. N_2O Emissions

a. Direct Emission

a. From Activated Sludge Tank:

By considering EF for activated sludge tank as 0.016 g N_2O-N/g Ninfluent [27,87,89]. N influent is considered as 8 gN/PE/d as discussed in mass balance section, and daily N_2O emission from this step is calculated as 0.128 gN2O-N/PE/d.

b. From Sludge Stabilization and Dewatering in Sludge Reed Bed:

EF sludge reed bed is considered as 0.00023 g N_2O-N/g Nsludge [62]. N value for digested sludge was calculated as 1.8 gN/PE/d in mass balance title. Therefore, emission from this step is calculated as 0.00032 g N_2O-N/PE/d.

b. Indirect Emission:

Indirect emission from N_2O is caused by water bodies and calculated by considering emission factor for water bodies and N content in effluent N effluent which is calculated in mass balance section is 2g N/PE/d and EF water bodies is 0.005 g N_2O-N/g N effluent [27]. Emission caused by this step is 0.01 N_2O-N/PE/d.

c. Total N2O Emission

Total N_2O emission is the sum of all the individual emissions

Table 13: Daily N2O Emission

DIRECT EMISSION	
N_2O Emission Source	**Emission Amount (gN_2O/PE/d)**
From activated sludge tank	0.128
Sludge stabilization and dewatering in Sludge Reed Bed	0.00032
INDIRECT EMISSION	
From receiving water bodies	0.01
Total	0.138

Total daily N_2O emission is calculated as 0.138 g/PE which corresponds 50.485 g/PE annually. And by using GWP factor from Table 3 yearly CO_2e is found as 13.378 kg/PE.

3.1.1.3.3. Infrastructure Related Emissions

This emission includes construction, regular renovation and disposal and is evaluated for both sewer system and WWTPs.

a. Emission caused by sewer system construction

In order to calculate the emissions accurately it's important to note that detailed information regarding sewer pipe lengths and sizes is not easily accessible on a European Union scale. As a result, in the reference study they rely on the OECD model equations [32] to make estimations. These equations are formulated based on the PE capacity of every WWTPs listed in the database maintained by the European Commission [91].

Since our WWTP serves 800000 PE, the pipe length per person can be considered as 0.75 m/PE, based on a reference study where different pipe length calculation formulas are proposed according to various PE numbers. The construction emissions for the sewer system are calculated using an emission factor provided by the OECD, which is 10,650 kg CO_2e per kilometer per year. Therefore, the total emissions for constructing the sewer system are calculated as 7.988 kg CO_2e/PE/year. This calculation considers the PE capacity, length, and diameter of the sewer pipes, and depends on the pipe material, pipe size, and catchment size of the sewer system.

b. Emission caused by WWTP construction

For the construction and regular renovation of the WWTP itself, the emission factor used is 3.3 kg CO_2e/PE/year for plants serving over 500000 PE [90].

c. Total Infrastructure Emissions

Combination of the emissions from the sewer system and WWTP construction gives the total emission from this step which is 11.288 kg CO_2e/PE/y.

3.1.1.3.4. Energy Consumption Related Emissions

Emissions related to energy consumption are indirect and include emissions caused by electricity and thermal energy consumption. In order to estimate these emissions energy consumption of the plant and their emission factor need to be known. Electrical energy requirement was calculated as 23.39 kWh/PE/y while thermal energy requirement was 19.49 kWh/PE/y in the 'Biogas Production and Energy Balance' section. Here energy produced by CHP system wasn't considered as it is accounted avoided emission section. For emission factors, the report called 'Efficiency and decarbonization indicators in Italy and in the biggest European Countries Edition 2023' is used. By implementing the value of 0.386 kgCO_2e/kWh and 0.404 kgCO_2e/kWh, emissions are calculated as 9.036 kgCO_2/PE/y and 7.882 kgCO_2e/PE/y for electrical and thermal energy consumption, respectively. Therefore, the total emission caused by energy consumption per year is 16.918 kg CO_2e/PE/y.

3.1.1.3.5. Chemical Consumption Related Emissions

In the baseline scenario, it is assumed that chemical precipitations are used to remove phosphorous and this process causes indirect GHG emission and calculated by using EF of chemical material used. In this study usage of ferric chloride ($FeCl_3$) is considered with the emission factors of 0.826 g CO_2e/g $FeCl_3$ [62]. In order to calculate the emission caused by the chemical it was important to estimate the amount of chemical used which is explained in the following paragraphs.

Amount of $FeCl_3$ used is related to chemically bounded P amount in the plant which can be calculated by considering P amount in influent, effluent and biologically bounded. Quantity of influent and effluent is 1 g P/PE/d and 0.15 g P/PE/d respectively as it was already discussed in the mass balance section. In order to calculate biologically bounded P, P fraction of digested sludge is assumed 0.01 gP/gCOD as it was assumed in other studies [62]. Since the amount of COD is assumed 23 gCOD/PE/d for digested sludge, biologically bounded sludge is calculated as 0.23 g P/PE/d. Then, below mass balance is used in order to calculate the amount of chemically bounded P (P chem) and obtained as 0.62g P/PE/d.

$$P_{chem} = P_{influent} - P_{effluent} - P_{biological}$$

It is assumed that an excessive amount of $FeCl_3$ (7.8 kg $FeCl_3$ or 2.7 kg Fe/kg P)[62] used and emission from this chemical is calculated as 1.463 kg CO_2e/PE/y.

3.1.1.3.7. Overall GHG Emissions

Total emission from the WWTP is calculated by summing direct and indirect emissions from CH_4, N_2O, infrastructure, energy consumption, and chemical usage and obtained as 54.916 kg CO_2e/PE/y. Avoided emission (10.489 kg CO_2e/PE/y) due to energy recovery from CHP system is subtracted from this value and net GHG emission is obtained as 44.427 kg CO_2e/PE/y.

3.1.2.Scenario Analysis

In this section, we will explore how enhancements could lower energy usage and GHG emissions emphasizing the advantages of technological advancements in WWTPs.

3.1.2.1.Scenario 1: Improved Aeration System

After reviewing the articles about aeration optimization methods in WWTPs, it is decided to focus on the combination of advanced aerator designs and advanced aeration control system since when they are combined it can lead to substantial improvements in efficiency and energy savings. As it was noted in literature review part, fine-bubble diffusers can lead to 20-40% energy saving while SCADA systems offer 15-25%. However, when combining them together there might be overlaps where benefits of one strategy reduce the potential saving from the another. Therefore, the reasonable estimate might be around 50% energy savings in the combined system which will reduce energy requirement for aeration is from 12.636 to

6.318 kWh/PE/y and this change will directly create a reduction in energy consumption of plant to 36.569 kWh/PE/y.

Reduction in electricity usage will decrease the indirect GHG emission caused by it. Since the EF for electricity is 0.386 kgCO_2e/kWh for Italy [57] indirect emission caused by energy consumption is calculated as 14.477 kg CO_2e/PE/y while it was 16.918 kg CO_2e/PE/y before. Overall GHG emission decreased from 44.427 kg CO_2e/PE/y to 41.986 kg CO_2e/PE/y.

3.1.2.2. Scenario 2: Biogas Improvement

After reviewing the articles discussing optimization techniques for biogas, the decision has been made to concentrate on co-digestion with organic waste since this approach has capability to greatly enhance biogas production. Even some studies explaining other methods suggested this method as future implementation due to its high potential for improvement.

The percentage of biogas improvement changes from one study to another since there are factors such as feedstock characteristics and operational conditions affecting the biogas improvement. For instance, Lima et al. found that co-digestion with organic waste could increase biogas production by 20-30% [42], Masłoń et al. stated that co-digestion with poultry waste yielding 82% increase in methane yield [37], Hagos et al. stated 25% to 400% [67] increase. Given these results, 35% is considered as a reasonable improvement percentage. This improvement will affect methane production in anaerobic digesters, which will then influence energy production and GHG leakage amount from the CHP system, leading to a change in overall GHG emissions.

Starting with methane production which was calculated considering biogas yield at the AD in the baseline, Scenario-2 assumes a 35% increase in biogas or methane production due to co-digestion which will lead to an increase in methane production from 10.01 L CH_4 /PE/d to 13.51 L CH_4 /PE/d. With increased methane production electrical and thermal energy production rise from 14.173 kWh/PE/y to 19.134 kWh/PE/y and 12.401 kWh/PE/y to 16.742 kWh/PE/y, respectively. Overall energy production will rise from 35.433 kWh/PE/y to 47.835 kWh/PE/y. These obtained values are used to calculate the avoided pollutant since, if it hadn't been produced, it would have needed to be purchased. Therefore, avoided pollutant loads are calculated by using emission factors of electrical and thermal energy production and obtained 14.160 kg CO_2 eq/y for this scenario while it was 10.489 kg CO_2 eq/y for baseline scenario. However, increased methane production also causes more methane leakage from the system where the value increased from 0.138 g CH_4 /PE/d to 0.186 g CH_4 /PE/d. Considering all these effects, GHG emissions decreased from 44.427 kg CO_2e/PE/y to 41.592 kg CO_2e/PE/y.

3.1.3. Scenario Comparison and Conclusion

Both scenarios, for enhancement bring about advantages in terms of saving energy and reducing GHG emissions when compared to the scenario. The Improved Aeration System option shows a decrease in energy usage and indirect emissions while the Biogas Improvement plan offers increase in energy generation and reduce in GHG emissions although it causes slight rise in methane leakage. These improvements underscore the potential of advanced technologies and methods to promote sustainable and effective wastewater treatment processes.

4.CONCLUSION

This analysis demonstrates the potential for GHG emission reductions and energy efficiency improvements in WWTPs through the implementation of advanced technologies.

The baseline scenario which involves comprehensive treatment processes was established using existing literature data to set a reference point, for energy consumption and GHG emissions during WWTP operations. Important factors such as water usage per individual, BOD, COD, and energy requirement per unit amount of wastewater were determined by considering that WWTP is located in Italy and serving 800000 PE and some other variables are decided according to general WWTP properties as benchmarks. This scenario played a role in comparing the benefits of the two optimization strategies.

The scenario of the Enhanced Aeration System illustrates the advantages of optimizing aeration through aerator designs and control systems, like SCADA. These enhancements have the potential to cut energy usage for aeration by up to 50% resulting in a decrease in energy consumption and indirect emissions. In particular, this approach reduces energy usage to 36.569 kWh/PE/year and lowers emissions from 16.918 to 14.477 kg CO_2e/PE/year leading to a net reduction of greenhouse gas emissions, to 41.986 kg CO_2e/PE/year. This case study demonstrates that making adjustments to aeration processes can lead to energy savings and environmental benefits.

The scenario of the Enhanced Biogas System revolves around improving biogas generation by combining waste with the existing sludge. With a 35% rise in methane output this method significantly increases energy recovery resulting in an energy production of 47.835 kWh/PE/year. Despite a slight increase in methane leakage the overall impact is a decrease in net GHG emissions, to 41.592 kg CO_2e/PE/year. These findings indicate that optimized biogas systems have the potential to save energy and enhance self-sufficiency of WWTPs emphasizing the importance of maximizing biogas production and effectively managing methane emissions.

Both scenarios demonstrate how WWTPs have an opportunity to decrease GHG emissions and enhance energy efficiency. The Improved Aeration System option leads to energy savings and reduced emissions while the Improved Biogas System choice greatly boosts energy generation and cuts down emissions. These results indicate that WWTPs can make progress, towards sustainability by embracing aeration technologies and maximizing biogas output.

Moreover, it is advisable to combine both biogas enhancement and improved aeration systems. This integrated method would optimize energy conservation and reduce emissions by leveraging the advantages of each technique. It's also crucial to install monitoring systems and adaptive management methods to maintain the efficiency of both approaches.

In conclusion, incorporating aeration techniques and improving biogas production methods offer an avenue, for wastewater treatment plants to enhance sustainability. By implementing these strategies significant energy savings, reduced carbon emissions and enhanced energy retrieval can be achieved. It is crucial to have support from policy frameworks and investments in technology to encourage the adoption of these optimization strategies. Additionally, ongoing research and development play a role in refining these technologies and exploring innovations like nutrient recovery and advanced sludge treatment methods. Embracing these advancements enables WWTPs to make a contribution, to initiatives aimed at combating climate change and promoting environmental sustainability.

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ACKNOWLEDGMENTS

I would like to express my deep appreciation to my supervisors Prof. Deborah Panepinto and Prof. Mariachiara Zanetti for all their invaluable advise, support, guidance and suggestions.

Special thanks to the Turkish Ministry of Energy and Natural Resources and the Turkish Ministry of National Education for the opportunities and financial support they have provided me.

I am endlessly grateful to my family and all my close friends in Turkey for always being there for me, showing their love to me and making me feel their support as if they were always right by my side.

Lastly, I want to extend a big thanks to my friends Solenn, Rapha, Mario, Deepak, Lorenzo and Cata, who are like precious gifts from Torino, for their support not only during this time but since we first met.