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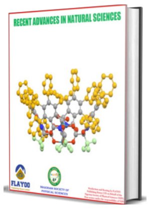

Wastewater treatment, greenhouse gas emissions, and our environment

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ABSTRACT

The reclamation and reuse of wastewater is a vital process that helps to address water pollution and scarcity problems. Nevertheless, wastewater treatment is also a significant source of greenhouse gases (methane, carbon dioxide and nitrous oxide). Methane, the most significant greenhouse gas is majorly emitted during anaerobic process, carbon dioxide from aerobic processes while nitrous oxide is associated with nitrification and denitrification processes. The increase in the level of these greenhouse gases is the main cause of global warming and climate change and has resulted in change in weather patterns, severe weather events, habitat loss and loss of wildlife. The adjusting of operating conditions, conversion of methane to fuel for energy production, carbon dioxide capturing are some highlighted methods to minimize the release of these heat-trapping gases from wastewater treatment plants. Also, methods of monitoring these GHG as well as the direct and indirect effects of climate change on the management of wastewater are also discussed in this review.

1. INTRODUCTION

The contamination of waterbodies is a global issue that deserves attention because of the damaging effects it poses to the environment and humans. The importance of proper handling of wastewater cannot be overemphasized and a key approach to manage water quality crises is the treatment and remediation of polluted water. Thus, the treatment of wastewater can therefore be considered a crucial part of a wholesome urban system.

Annually, approximately 380 billion cubic meters of wastewater are produced worldwide, and it is projected to rise by about 24% by 2030 and 51% by 2050 [1]. The treatment of polluted water plays a critical role in the sustainability of the environment as this process removes several dangerous chemicals and microorganisms that adversely affect mankind and animals. Nevertheless, the different procedures involved in the treatment of wastewater result in pollution associated with the emission of greenhouse gases (GHG). According to the United Nations World Meteorological Organization, the levels carbon dioxide, methane and nitrous oxide gases reached a new record high in 2021; an increase of 50% compared with 1990 levels [2]. Reports have stated that wastewater treatment plants (WWTPs) account for anthropogenic emission of 3-5% of global greenhouse gases [3, 4]. Methane is considered the most significant greenhouse gas as its global warming potential is more than that of carbon [5]. It is mainly associated with anaerobic processes of wastewater treatment. Initial projection reported global methane emissions at an average of 2.3 and 33 Tg/yr from municipal and industrial wastewater management [6–8]. Carbon dioxide con-

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tributions are majorly from aerobic processes and energy consumption in wastewater treatment plants [9]. Nitrification and denitrification processes in wastewater management release nitrous oxide into the atmosphere. Nitrous oxide is a potent greenhouse gas and is projected to be the most ozone layer depleting substance [10]. It accounted for approximately between 12-24 Tg/yr of global anthropogenic gas emissions from 2007-2016 and emissions from wastewater treatment accounted for 2.8% of the total anthropogenic sources [11, 12].

The discharge of these gases into the atmosphere is one of the major causes of climate change. Climate change is a change in the average weather patterns over a long time that defines the earth's climates. Climate change is a peril to the wellbeing of humans and our planet, and the negative effects predicted that would result from climate change are now taking place.

Numerous studies have explored the challenges of wastewater management [13–15] wastewater remediation and climate change [9, 14, 16–18] energy implications of climate change on wastewater management [1, 17, 19–21], greenhouse gas emissions from wastewater treatment plants [15, 22–24]. However, there is limited information on how wastewater management affects climate change. This review paper aims to discuss various wastewater treatment methods and the greenhouse gases they emit and propose strategies to mitigate the discharge and impact of these gases on the environment. Finally, it will present a comparison of these strategies, and current global emissions of greenhouse gases from selected wastewater treatment plants worldwide and address the problems associated with climate change and wastewater management.

2. WATER POLLUTION AND SCARCITY CRISIS

Water pollution may arise from various pathogens and chemicals introduced into waterbodies by untreated agricultural, industrial, and domestic wastewater. The inflow of these pollutants into water systems threatens access to safe water and causes environmental problems because of its toxicity to animal and plant life. The pollution of water bodies is the second most vital environmental concern along with air pollution and the major factors driving water pollution are population growth and urbanization. About 70% of the earth is made up of water, but only 3% is freshwater with two-thirds of that frozen in arctic and glaciers. With increased population and urbanization, world water demand is expected to rise by 55% by 2050 [25] and global urban population experiencing water scarcity is projected to double from 930 million in 2016 to 1.7-2.4 billion people in 2050 [26]. Clean water is an irreplaceable resource and access to safe water is critical for human survival and a sustainable ecosystem. For this reason, the proper management of water is essential. Managing water sustainably ensures water use in a way that accommodates current and future water demands. This also means that everyone is an actor in the ecosystem and because we depend on the resilience and renewability of ecosystem resources, communities must find means to adapt to the loading capacity afforded to them by their immediate ecosystem [27]. Sustainable water management practices include water resources and governance, urban water management, water management and food production, water and energy sustainability, water and sustainable human development, sustainable applications in hydrology and hydraulics and water and wastewater treatment [27–30]. Also, according to a United Nation policy brief, pollution prevention, safe use of wastewater, treatment of polluted water and restoration and protection of the ecosystem were listed as approaches to tackle water quality problems [31].

3. WASTEWATER TREATMENT AND REUSE

The depleting rate of freshwater combined with the rapid surge in population growth calls for continuous reclamation and reuse of wastewater to fulfil the requirements of clean water for communities. The treatment of wastewater involves a process that removes impurities from wastewater; this process enhances the quality of water to make it suitable for a specific purpose (domestic, irrigation, industrial use and water recreation) and or returned to the water cycle. According to reports, agriculture accounts for 92% of water consumption of which 70% are freshwater for irrigation purposes [32–34]. This impacts heavily on water crisis. Wastewater can be reclaimed and reused directly or indirectly for agriculture, landscape irrigation, and recreational purposes. Direct usage involves the channeling of treated wastewater into some type of water system like the irrigation of a golf course. Treated wastewater can be used indirectly when it is discharged into ground water and later collected for use.

In a wastewater treatment plant, contaminated water passes through various stages to become purified. The three major stages (Figure 1) are the pre-treatment/primary treatment stage (removal of debris using screens, skimming tanks, and grit chambers), secondary treatment (removes soluble organic matter and suspended organic solids using microorganism under aerobic, anaerobic and or anoxic conditions), tertiary treatment (further purification performed on wastewater susceptible to pollution) [35]. Sludge collected from these treatment steps is further treated and disposed of.

Overall, in a conventional wastewater treatment plant, a combination of techniques is used in the various stages which could be physical, chemical, biological and or physicochemical [36]. They include chemical precipitation, coagulation/flocculation, floatation, chemical oxidation (with ozone, hypochlorite, and hydrogen peroxide), biologically activated sludge, microbial treatment, enzymatic decomposition, adsorption, ion-exchange resins, catalytic and thermal oxidation, electrolysis, membrane filtration, and advanced oxidation processes [37].

4. WASTEWATER TREATMENT AND THE ENVIRONMENT

Although the treatment of wastewater gives us access to an invaluable resource we must, however, appreciate its drawbacks and implement solutions to minimize the negative environmental problems it poses. The process of treating polluted water directly emits relatively substantial amounts of methane, nitrous oxide and carbon dioxide into the atmosphere while indirect emissions result from energy generation, chemical use and transportation. Current studies have found that wastewater treatment plants can be a source of greenhouse gas emissions, contributing to air pollution and climate change [17, 38, 39]. Similarly, studies have implicated the emission of greenhouse gases and energy consumption from wastewater treatment facilities as the primary factors that have a significant effect on global climate change [15, 40, 41]. Global warming is an established phenomenon that

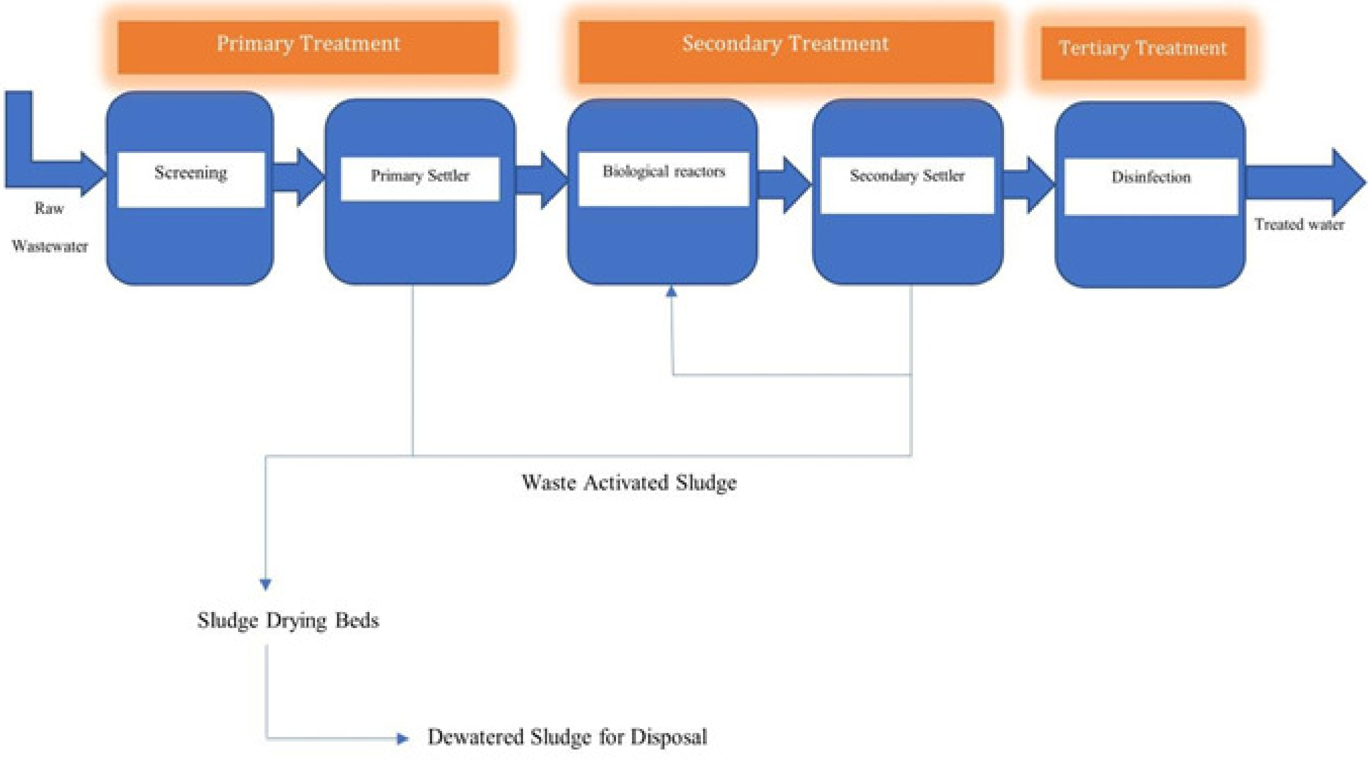

Figure 1. Schematic illustration of a conventional wastewater treatment plant.

results in rising sea levels, changes in weather patterns, and more frequent and severe extreme weather events. Changes in snow formation and melting for instance could lead to altered river flow, droughts, floods, and other devastating impacts. Also, the constant rise in global temperature has resulted in extinction and habitat loss by different species and wildlife. The current levels of the major greenhouse gases are presented in Table 1.

Wastewater treatment plants may be accountable for 23% more greenhouse gas than earlier evaluated because of the presence of fossil fuels in detergent-laden water from municipal and industrial wastewater [43]. The process of treating wastewater in the United States resulted in an estimated 21.1 and 30.9 million metric tons of CO2 equivalent of CH4 and N2O respectively in 2021 which accounts for 0.7% of the total greenhouse gas emissions in the country [44]. According to a report by Parravicini et al the estimated cumulative emission of greenhouse gases from European urban wastewater sector is about 35 million tons CO2e/yr [45]. Sharawat *et al.* documented that the energy consumption of a wastewater treatment plant in India amounts to 0.26 kW h/m3 of the treated wastewater. It stated that the overall share of electrical energy consumption is 84%, and 78% of the electrical energy is consumed in the aeration process. The direct and indirect greenhouse gas emissions from the wastewater treatment plant amount to 105 tCO2e/yr and 1316 tCO2e/yr, respectively [46]. In China, the results of a study showed that GHG emissions from WWTPs more than tripled from about 13 Mt CO_2e in 2005 to about 31 Mt CO2e in 2020 [47]. These emissions are associated with both the energy and chemical used in wastewater treatment and the breakdown of organic materials in the water treatment plant. A vital step towards achieving our environmental goals is to reduce the carbon footprint incurred by wastewater treatment plants. We can achieve sustainable wastewater treatment processes by understanding the emission sources, comparing technologies based on carbon footprint, reducing energy consumption and using sustainable energy sources [48].

5. GREENHOUSE GASES, SOURCES IN WWTPS, AND MITIGATION STRATEGIES

5.1. METHANE

Methane is the second most important GHG with a shorter lifespan in the atmosphere compared with carbon dioxide, however, it has a global warming potential eighty-six times more than CO2 on a 20 year' time scale [49]. In the atmosphere methane directly contributes 0.5 Wm^{-2} to total radiative forcing by long lived greenhouse gases [50] and its production of tropospheric ozone and stratospheric water vapour indirectly adds about 0.2 Wm^{-2} to its climate forcing [51]. The wastewater treatment sector is a significant source of methane, contributing about 6% of global anthropogenic methane emissions [52]. A recent study has stated that wastewater treatment plants emit about twice as much methane than formerly thought [53]. The primary source of methane in wastewater treatment facilities is from anaerobic conversion of organic materials to methane and carbon dioxide by methanogens. According to studies, methane was majorly detected in the sludge line units (the primary sludge thickener, sec-

Table 1. Current trends of main greenhouse gases from Global Atmosphere Watch in-situ observational network for GHGs. Units are dry-air mole fractions, and uncertainties are 68% confidence limits [42].

	CO2	CH4	N2O
Global mean abundance (2022)	417.9±0.2 ppm	193±2 ppb	335.8±0.1 ppb
Relative abundance in 2022 compared with 1750	150%	264%	124%
Absolute increase from 2021-2022	2.2 ppm	16 ppb	1.4 ppb
Mean absolute increase over the past 10 years	2.46 ppm/yr	10.2 ppb/yr	1.05 ppb/yr

ondary sludge thickener, digested sludge tank, dewatered sludge tank and leakages from the digester) where anaerobic digestion occurs [17, 53–55]. Approximately 72% of methane is emitted from these units while dissolved methane in biological reactors accounts for the rest and can be ascribed to wastewater containing dissolved methane which is not completely removed by the biological system [55, 56]. During anaerobic degradation the following processes have been identified to lead to methane formation. The first process is the hydrolysis of proteins, carbohydrate and lipids in the suspended organic solids to sugars, amino acids and fatty acids. These (sugars, amino acids and fatty acids) are further degraded by fermentative organisms or anaerobic oxidizers to either acetate, hydrogen or volatile acids (propionate, butyrate). The final step is methanogenesis/bio-methanation where acetate and hydrogen are converted to methane by the action of acetotrophic and hydrogenotrophic methanogens respectively. The process is illustrated in Figure 2.

The reduction of methane emissions associated with wastewater treatment will be significant in attaining global climate mitigation goals [57], and if effectively managed methane could serve as a valuable fuel, natural gas and carbon source for methanotrophs. Most wastewater treatment facilities encourage the production of methane (from anaerobic digesters) for energy, however, methane losses and leakages across the treatment system remains an uphill task. Yoshida *et al.* recorded a wide range of methane losses in a WWTP; higher methane emissions were associated with operational problems like digestor foaming as well as changes in environmental conditions such as temperature and humidity [58]. Methane emissions can be attributed to its ebullitive, and diffusive nature occurring in several places and vary depending on the characteristics of the wastewater, the process and configuration of the plant, and operational conditions [53, 58]. The first approach to curb methane leakages is to cover thickening sludge tanks appropriately and their emissions captured by hoods which could be used as fuel for energy production. Some biological processes have been documented that oxidizes methane to carbon dioxide and this minimizes the total GHG in terms of carbon dioxide equivalents since methane has a higher warming potential compared with carbon dioxide. In the presence of oxygen, methane can be oxidized with methanotrophs or under anaerobic conditions with methanogens using nitrite, nitrate, sulphate or manganese(iv) as electron acceptor as shown in equations (1)-(5) [61–66].

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad \Delta G^\circ = -859\ kJ\ mol^{-1} \tag{1}$$

$$3CH_4 + 8NO_2^- + 8H^+ \rightarrow 3CO_2 + 4N_2 + 10H_2O \qquad \Delta G^\circ = -928\ kJ\ mol^{-1} \tag{2}$$

$$5CH_4 + 8NO_3^- + 8H^+ \rightarrow 5CO_2 + 4N_2 + 14H_2O \qquad \Delta G^\circ = -765\ kJ\ mol^{-1} \tag{3}$$

$$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O \qquad \Delta G^\circ = -16.6\ kJ\ mol^{-1} \tag{4}$$

$$CH_4 + 4MnO_2 + 7H^+ \rightarrow HCO_3^- + 4Mn^{2+} + 5H_2O \qquad \Delta G^\circ = -556\ kJ\ mol^{-1} \tag{5}$$

Zhu *et al.* and Molina-Macias *et al.* reported on the successful removal of methane with aerobic and anaerobic methane oxidation coupled with a denitrification process which uses methane as the electron donor [61, 67, 68]. This process not only removed methane, nitrite, and nitrate but also eliminated the need for electron donor for the denitrification processes thereby reducing the cost of external carbon sources [56, 69]. Also, methane loads from the sewer system, which have been projected to account for 1% of influent chemical oxygen demand (COD) load and are mainly oxidized in the activated sludge tanks could be exploited with these technologies to further decrease methane emissions from wastewater treatment plants [55]. Remnants of methane after the biological process can be sent to post combustion processes [70].

5.2. CARBON DIOXIDE

Carbon dioxide is the most abundant GHG accountable for about three-quarter emissions. According to IPCC, carbon dioxide is responsible for 76% of global GHG emissions [71]. The major source of CO_2 emissions is from human activities such as burning fossil fuels, solid waste along with deforestation. From 2020 to 2022, the increase in global atmospheric CO_2 concentration was recorded to be 4.66 ppm. A decrease of 0.26 ppm observed in 2022 have been attributed to absorption of CO_2 by terrestrial ecosystem and the ocean many years after a La Niña event [42]. The development of an El Niño event in 2023 will however, have a significant effect on GHG concentrations. Wastewater treatment facilities are important sources of CO_2 as they contribute about 3% to global GHG emissions [72]. Montieth *et al.* reported a CO_2 emission range of 5 – 994 g per cubic meter of treated wastewater with the highest emissions coming from extended aeration and aerobic digestion [73]. Indirect emissions of CO_2 emanate from energy consumption of the various devices

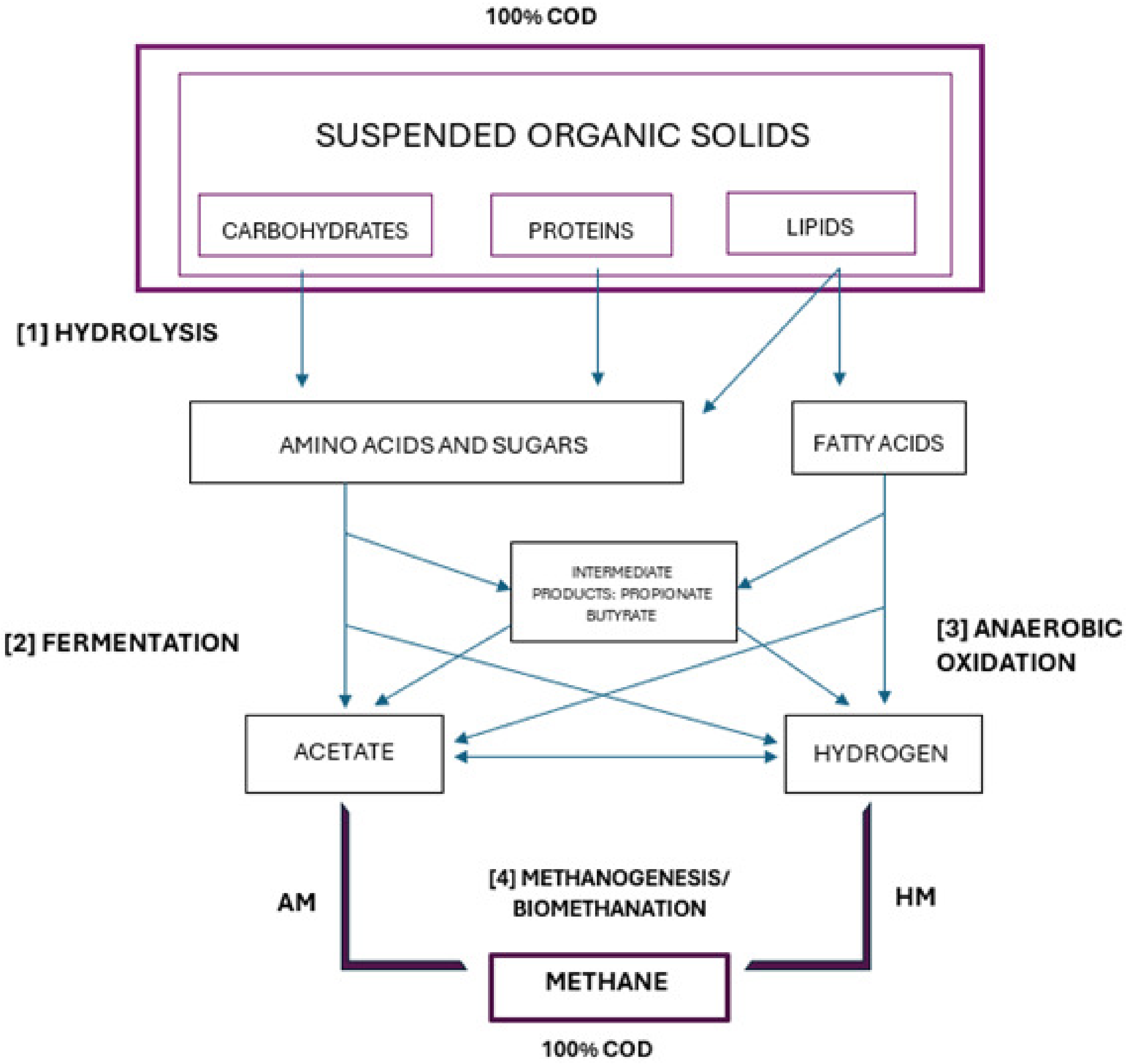

Figure 2. Proposed methane production pathway in anaerobic digestion [59, 60]. AM: Acetotrophic methanogens, HM: Hydrogenotrophic methanogens.

used when operating WWTPs, production and transportation of chemicals and fuels as well as waste disposal while direct emissions are majorly from aerobic processes in wastewater treatment. Even though direct emission of CO_2 during wastewater treatment is considered a carbon neutral process, evidence have shown that 4-14% of the total organic carbon from the wastewater influent is from fossil origin [74, 75].

Currently, the major aim of the wastewater industry is to decrease carbon emissions. Campos *et al.* stated that increasing solid retention time during sludge activation increases the rate of COD oxidation to CO_2 and this reduces the overall sludge production [56]. This in turn decreases production of methane and the associated CO_2 emission. Conversely, reducing retention time improves energy efficiency of the WWTP and thereby decreases indirect CO_2 emissions. It is therefore important to apply the shortest retention time possible to obtain optimum effluent quality. The production of biochar from sludge [76–79], application of constructed wetlands [80, 81], microbial electrosynthesis [82–86], microalgae cultivation [85, 87–89] and microbial fuel cells and carbon capture (MFC/MCC) [90–92] are recent technologies that have been engineered to capture and mitigate carbon from wastewater treatment plants. Microbial fuel cells can convert chemical energy from wastewater to electrical energy while decomposing organic matter while MEC partially reverses the process to generate hydrogen or methane. In a recent report by Dong *et al.*, a new device that couples MEC with water

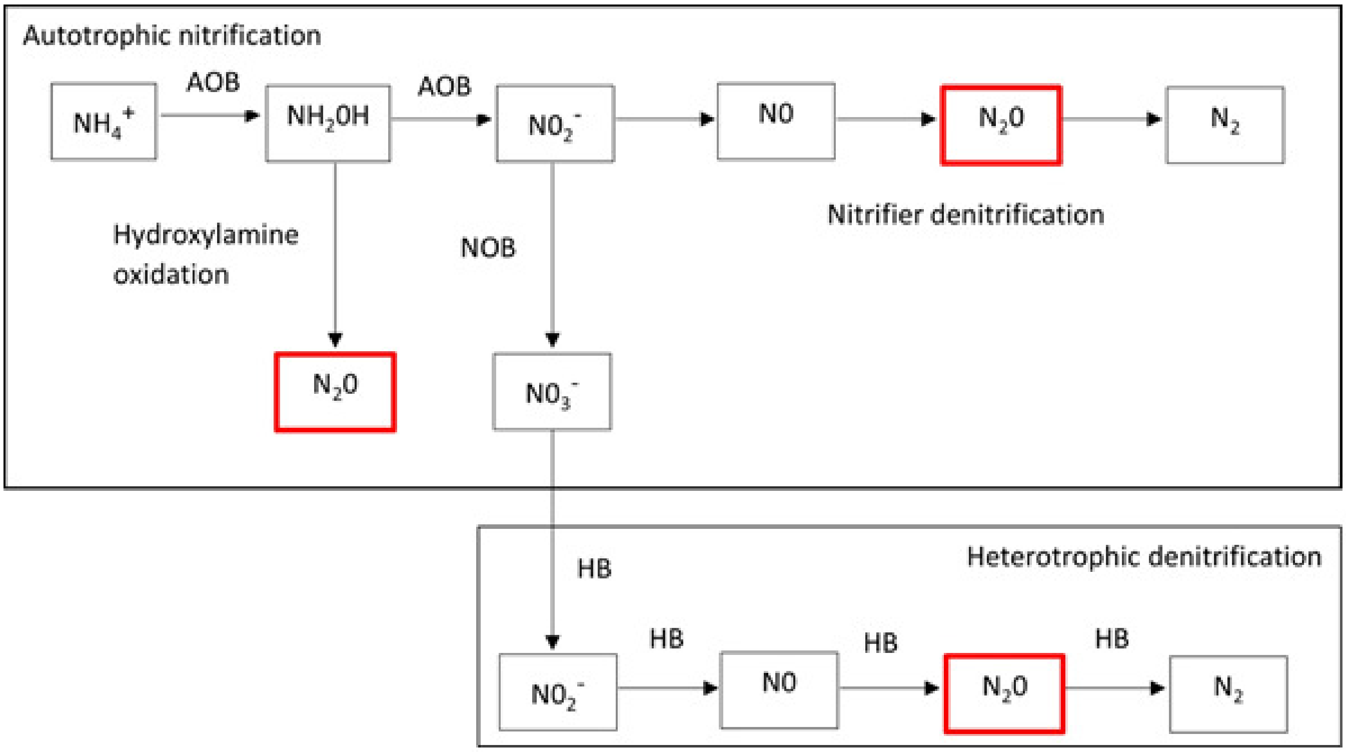

Figure 3. Major pathways for biological generation of N2O during wastewater treatment; AOB (ammonia-oxidizing bacteria), NOB (Nitrite-Oxidizing Bacteria), HB (Heterotrophic Bacteria).

Table 2. Conditions favoring N_2O emissions in wastewater treatment plants [104, 110].

Low oxygen levels (nitrification)	-limited aeration
	-high organic load coupled with insufficient oxygen
High oxygen levels (denitrification)	-excess aeration during nitrification stage
High nitrite (nitrification)	-low solid retention time
	-limited aeration
	-low pH
	-increased ammonium concentration
	-low temperature
High nitrite (denitrification)	-insufficient COD
	-low pH
	-Nitrite from nitrification stage
	-high temperature
Low COD/N (denitrification)	-efficient pre-sedimentation
	-influent composition (low biodegradable organic carbon)

electrolysis was developed [93]. The microbial water electrolysis cells (MWEC) achieved industrial-level high current density, and fast hydrogen production with low energy consumption compared with MEC. These technologies are quite promising in combating the effects of climate change by reducing carbon footprint however, most of them are still at lab-scale and require high operating capital [94]. Direct air capture technologies (DAC) trap CO_2 directly from the atmosphere for storage and or utilization. According to the International Energy Agency (IEA), twenty-seven DAC plants have been commissioned to date globally, capturing about 0.01 $MtCO_2$ per year and if all planned facilities were to advance, DAC placements would reach the required 2050 Net Zero Emissions by 2030 or about 75 $MtCO_2$ per year [95]. Very recently, the USA installed its first direct-air capture facility that will be capable of removing 1000 tons of CO_2 from the atmosphere per year [96]. The facility which runs on renewable energy uses limestone to trap CO_2 from the atmosphere; the extracted pure CO_2 is then stored and sent to concrete companies. Another such facility in Iceland withdraws 4000 tons of CO_2 from the atmosphere per year. Having such a facility situated around WWTPs will go a long way in minimizing the amount of CO_2 in the earth's atmosphere. The installation and opera-

Table 3. A comparison of some mitigation strategies of GHGs in WWTPs.

GHG	Mitigation strategy	Cost	Efficiency	Scalability
Methane	Anaerobic digestion	Moderate to high initial investment, but operational costs can be offset by energy production.	High efficiency in reducing methane emissions by converting organic waste into biogas. Can reduce emissions up to 90%.	Highly scalable, suitable for both small and large WWTPs.
	Aerobic treatment	Lower initial cost compared to anaerobic systems, but higher operational costs due to energy requirements	Moderate efficiency in methane reduction, as it prevents methane formation rather than capturing it	Scalable, but energy-intensive, making it less suitable for large-scale applications
	Methane leak and repair	Low to moderate, depending on the frequency and technology used for detection	High efficiency in preventing emissions	Easily scalable, applicable to any size of WWTP
	Methane capture and utilization	Moderate to high, depending on the infrastructure required for capturing and utilizing methane	Very high, as it directly captures methane emissions and converts them into energy	Scalable, but more suitable for larger facilities with significant methane production
	Advanced oxidation processes	High, due to the need for specialized equipment and chemicals	High efficiency in reducing a wide range of pollutants, including GHGs	Suitable for large-scale industrial applications
Carbon dioxide	Carbon capture and storage	Very high due to the need for CO2 capture and compression technologies and requires significant energy	Capable of capturing up to 90% of CO2 emissions from large sources	More suitable for large-scale plants with significant emissions
	Aerobic treatment processes	Moderate initial investment with higher operational costs due to energy requirements for aeration	Effective in reducing CO2 emissions by promoting the breakdown of organic matter through aerobic bacteria	Suitable for small to medium-sized plants
	Algal carbon capture	Medium to high. Depending on the size and technology used for algal ponds. Energy inputs are relatively low once system is established	Can capture around 50-70% of CO2 emissions from treatment ponds	Better suited for WWTPs with large land availability and warm climates
	Constructed wetlands	Low to moderate depending on design and scale	Moderate efficiency in reducing CO2 emissions through natural processes and plant uptake	Highly scalable, suitable for small communities and decentralized systems
	Energy efficiency improvements/use of renewable energy	Medium to high, depending on the scale of the plant and technology used but can decrease operational cost due to energy savings	Reduces CO2 emissions from energy use by up to 20-30%	Highly scalable across different WWTP sizes
	Biochar production	Moderate, with potential revenue from biochar sales	High efficiency in sequestering carbon by converting organic waste into biochar through pyrolysis	Suitable for small to medium-sized plants
Nitrous oxide	Process control optimization through improved oxygen management	Medium, depending on the scale of the plant and the need for system upgrades but low operational cost due to energy savings	Effective in reducing N_2O emissions by maintaining optimal dissolved oxygen levels. Can reduce N2O emissions by 20-40% depending on the system and existing inefficiencies	Scalable across all plant sizes, especially useful for medium and large WWTPs where aeration is a major energy consumer

Partial nitrification/anaerobic ammonium oxidation	Moderate to high initial investment, but operational costs are relatively low due to reduced energy requirements	High efficiency in reducing N2O emissions (80-90%). Significant reductions in energy use and CO2 emissions (around 50% lower than conventional nitrification/denitrification processes)	Suitable for medium to large wastewater treatment plants with high ammonia loads
Algal based treatment	High, particularly for photobioreactor systems but medium operational cost as agal systems require light and CO$_2$ but minimal energy compared to conventional processes	Can reduce N2O emissions by up to 70%	Limited scalability, as algal systems require large land areas and consistent light sources, making them impractical for urban WWTPs
Methanol step dosing	Moderate, depending on the availability and cost of methanol	High efficiency in reducing N2O emissions by providing a consistent carbon source for denitrification	Suitable for medium to large-scale plants

tion of renewable energy systems are necessary for the energy-intensive wastewater treatment sector. The use of solar photovoltaic systems has been reported to reduce carbon emissions by up to 40% and integrating renewable energy sources (biogas, solar energy) could provide 88% of annual energy requirements of WWTPs [97, 98]. Campana *et al.* developed a 100% renewable WWTP model by integrating photovoltaic systems, wind turbines, multi-energy storage technology, and reverse osmosis tertiary treatment to absorb power production [99]. The model was applied to different WWTPs worldwide and the best model design involved creating a system where 70% of energy is from renewable sources which resulted in the lowest overall cost when considering the present value of all future costs and saving.

5.3. NITROUS OXIDE

Nitrous oxide is a powerful greenhouse gas with a global warming capacity 265 times that of CO$_2$ and an atmospheric lifetime of 114 years [100]. It is chemically inert in the troposphere where it spends most of its lifetime before moving to the stratosphere where it eventually destroys stratospheric ozone. Research has shown that 40% of total N$_2$O emissions are from human activities such as agriculture, land use, combustion of fossil fuel and solid waste, industrial activities as well as wastewater treatment [101]. In 2021, N$_2$O emissions accounted for 6% of all GHG emissions from human activities in the USA and 5% of anthropogenic source of N$_2$O are from wastewater treatment facilities [102], [103]. Globally, the wastewater treatment sector is responsible for 3% of anthropogenic nitrous oxide emissions[104]. In wastewater treatment plants, nitrous oxide is produced in area of high biological oxygen demand and low oxygen, such as the influent lines, settling tanks, activated sludge units and emitted primarily in the aerobic compartments mainly due to active stripping and ammonia-oxidizing bacteria [105]. The two major pathways are autotrophic nitrification (via nitrifier denitrification and or hydroxylamine oxidation) and heterotrophic denitrification as shown in Figure 3. The input of heterotrophic denitrifying bacteria is only important when nitrite and or are present in the anoxic stage [106]. The involvement of both pathways is yet to be fully understood because nitrous oxide can be formed in the anoxic stage and then be stripped to the gas phase in the aerated zone. However, there is strong evidence that both nitrifier denitrification and breakdown of hydroxylamine oxidation intermediates are always involved [107]. Nitrous oxide can also be produced chemically in reactions involving hydroxylamine, nitrite and nitroxyl compounds [108]. Such reactions have been suggested to happen in wastewater treatment plants; the formation of nitric oxide and nitrous oxide in activated sludge by ferrous iron [109]. The significance of this chemical pathway in wastewater treatment plants is, however, yet to be established.

According to studies the factors that affect the emission of N$_2$O from wastewater treatment systems are the concentration of dissolved oxygen, transient anoxic and aerobic conditions, shift in process conditions, nitrite accumulation, pH, substrate composition, COD/N ratio, and temperature [104, 107]. A summary of these conditions is shown in Table 2. Hence, understanding the reactions and factors affecting N$_2$O production in wastewater treatment facilities can help mitigation through improved plant design and operation.

Similarly, optimizing the above-mentioned process conditions will be a very effective way to minimize the emission of nitrous oxide from wastewater treatment plants. Several laboratory studies have demonstrated various strategies to minimize N$_2$O emissions. In a study by Yang *et al.*, they showed that N$_2$O emissions can be reduced by 50% when NH$_4$ and NO$_2^-$ are sustained at low levels via step feeding [111]. High solid retention times also support low ammonia and nitrite concentrations, higher dissolved oxygen and increased ammonia-oxidizing bacteria biomass concentration. These conditions have been suggested to minimize N$_2$O production in nitrification processes [56, 104, 112]. During denitrification, high dissolved oxygen hinders N$_2$O reductase activity which leads to accumulation of N$_2$O [104]. In a study by Law *et al.* an increase in pH from 6-8 was observed to have a major impact on the rate of ammonia oxidizing bacteria enriched culture which yielded maximum N$_2$O production at pH 8 in a partial nitritation system [113]. Adding methanol as an external carbon source prevented 95% N$_2$O emissions in both aerobic and anoxic phases [114]. The use of large bioreactors and influent flow-balancing set-ups have been proposed to enable systems with the capacity to buffer loadings and minimize the risk of transient oxygen loss [107]. Nitrous oxide emissions can also be minimized by limiting nitrous oxide stripping by aeration to promote consumption by microorganisms [56, 115]. A mitigation strategy implemented in a full-scale study of a WWTP run on sequencing batch reactor resulted in a 35% reduction of N_2O emissions and 20% saving on aeration energy. The authors attributed N_2O reduction to implementing a multi-pathway N_2O production mathematical model based on lowering dissolved oxygen levels [116]. This shows that full-scale mitigation is feasible, and laboratory studies will most likely be effective in full-scale plants. Another full-scale study also ascribed the 10% total carbon footprint reduction to drop in N_2O emissions via decreased dissolved oxygen levels and enhanced mixed liquor recirculation [117]. Algal technologies studied for bioremediation of wastewater could also present solution for nitrous oxide emissions in WWTPs [118–120]. Also, the use of membrane aerated bioreactors has been reported to minimize nitrous oxide emission with efficient nutrient removal [121, 121, 123] even on a full-scale WWTP [124]. A summary of a comparison of mitigation measures for GHGs in WWTPs is presented in Table 3.

6. MONITORING GREENHOUSE GAS EMISSIONS FROM WWTPS

WWTPs contribute significantly towards emission of anthropogenic GHG and apart from applying measures to minimize their emission, it is also vital to monitor these emissions in order to understand how much they impact the environment. One way to keep track of these emissions is to link the emission of GHGs with a particular activity in the plant in order to appropriately estimate the quantity of emissions. In addition, proper documentation/record keeping is important for future reference. The GHG Protocol Corporate Standard defined three scopes to examine when estimating the GHG emissions of a facility/company [125]. **Scope 1-** includes direct emissions from sources owned or controlled by the company such as on-site energy, natural gas, emissions from fleet of vehicles as well as emissions released during industrial processes. **Scope 2-** represents indirect emissions from purchased or acquired energy. Nevertheless, if the reporting facility generates its own energy on-site from owned or controlled sources, then emissions associated with energy generation are categorized as direct scope 1 emissions. **Scope 3-** comprises all indirect emissions that arise as a result of the activities of the reporting company, i.e., emissions from sources not owned or controlled by the company. An example is the emission of GHG that occurs during the production of chemicals that are used in WWTPs. In the U.S., the Greenhouse Gas Reporting Program (GHGRP) tracks gas emissions from various sectors, including industrial waste landfills, municipal solid waste landfills, wastewater treatment facilities. The GHGRP provides data on the total reported emissions from subsector, trend of annual reported GHG emissions, location and emissions for each reporting facility in the waste sector [126].

In quantifying GHG emissions, field-based measurements are vital for comprehensive GHG assessments as they provide direct estimates of GHG emissions and help build assumptions for models and develop emissions factors [127]. Estimation models are also used such as empirical models, life-cycle assessment models, process-based models and proxy indicators [128–131]. The combination of empirical models to describe GHG emissions and mechanistic models to describe the performance of a WWTP have also been documented to estimate GHG emissions of WWTPs [129, 132]. A process model developed by Bridle *et al.*, detailed some selected direct and indirect GHG emission sources in WWTPs and they include CO_2 and NO_2 emissions from biotreatment, CO_2 and CH_4 from sludge digestion, energy use for mixing, pumping, and aeration which leads to CO_2 emissions, sludge disposal/reuse, truck emission trip,CO_2 emissions mineralization, GHG emissions from chemical use and power credit from biogas use [133, 134]. Table 4 presents an inventory of the emission of GHGs from different wastewater treatment plants along with some country inventory.

7. THE IMPACT OF CLIMATE CHANGE ON WASTEWATER TREATMENT PLANTS

Because our world cannot do without treated water, we must recognize how climatic events worsened by GHGs emissions affect wastewater treatment plants. It can be said that climate change has a two-fold outcome on water resources and wastewater treatment facilities. Change in weather patterns, extreme weather events affect operational processes in WWTPs and because of water scarcity, the reclamation and reuse of wastewater has become inevitable as climate change advances. Then again, the emission of heating trapping GHGs from wastewater treatment adds to the problem of climate change.

Climate change is a major concern for wastewater treatment facilities. According to Zouboulis and Tolkou, rainfall, snowfall, rain on snow event (generates flood), storm surge, extreme temperatures, rise in sea levels, drought, ice, frost and wind speed are particularly significant climate factors that affects wastewater treatment plants [18]. The management of wastewater can be disrupted by these climatic factors. Extreme events can overwhelm the capacity of sewer systems and can result in untreated effluents overflowing the treatment system and pouring into surrounding waterbodies. The impacts of climate change can be directly associated with climate change on wastewater infrastructure or indirectly associated with climate change such as the decrease in water usage associated with water conservation [18]. A reduction in water use reduces the water that flows into wastewater collection and treatment systems, meaning a decreased water volume but same waste concentration. This can result to inadequate water to move waste and solid through the system; an increase in viscosity of wastewater and difficulty in system cleaning creating possible hydraulic and corrosion problems [18, 145]. The impact of intense rainfall and drought can directly affect the working of a WWTP by causing sanitary sewer overflow and reduced river and stream base flow respectively. Intense rainfall can cause heavy inflow of water into sewer systems resulting in overload of sewers; thus, allowing raw sewage into homes and surrounding waterbodies as it escapes sewer systems. This situation is known as sanitary sewer overflow. Increased frequency of this event is likely to create more instances of serious environmental contamination and health problems [146]. In drought prone areas, climate change can potentially cause a decrease in stream and river base flow. Base flow is used to determine effluent requirements by the WWTP and as this decreases, effluent requirements become more severe and may the installment of other treatment amenities in the WWTP to meet those requirements [18]. De-

Table 4. Greenhouse gas emissions of some selected wastewater treatment facilities and country inventory.

Wastewater treatment facility	CH_4	CO_2	N_2O	Country	Reference
Antalya City Hurma WWTP – 210,000 m^3/day Lara WWTP - 62,500 m^3/day	47,029 tCO_2eq/yr	52,423 tCO_2eq/yr	33,006 tCO_2eq/yr	Türkiye	[135]
Turkish Greenhouse Inventory	2018- 112.15 $ktCO_2eq$ 2019-113.32 $ktCO_2eq$ 2020-115.09 $ktCO_2eq$ 2021-118.86 $ktCO_2eq$	- - - -	2018- 7.38 $ktCO_2eq$ 2019- 7.46 $ktCO_2eq$ 2020-7.69 $ktCO_2eq$ 2021-7.91 $ktCO_2eq$	Türkiye	[136]
Southwest Germany Ruelzheim WWTP – 5000 m^3/day Bellheim WWTP – 14700 m^3/day	*491.365 g-C d^{-1}	-	*15.748 g-N d^{-1}	Germany	[4]
Southside of Guelph City	133,200.18 CO_2eq.kg/day	17495.54 CO_2eq.kg/day	1924.48 CO_2eq.kg/day	Canada	[137]
Several WWTPs in various parts of China	2018- 53-54 Mt CO_2eq/yr 2019- 55-56 Mt CO_2eq/yr	2018- 57-58 $MtCO_2eq/yr$ 2019- 60-61 $MtCO_2eq/yr$	2018- 48-49 $MtCO_2eq/yr$ 2019- 51-52 $MtCO_2eq/yr$	China	[15]
Himachal Pradesh Sewage Treatment Plants < 1 MLD (24 Nos), 1-3 MLD (26 Nos), > 3 MLD (9 Nos)	3103.3 tCO_2eq/yr	2522.7 tCO_2eq/yr	9303.4 tCO_2eq/yr	India	[138]
Mumbai Metropolis Sewage Treatment Plan (100 MLD; treats ~35 MLD)	0.002 $kgCO_2eq/m^3$	-	0.011 $kgCO_2eq/m^3$	India	[139]
Apulian, Southeast Italy 183 WWTPs; 4,807,354 PE	69.0 $KgCO_2$/PE·y	95.9 $KgCO_2$/PE·y	72.7 $KgCO_2$/PE·y	Italy	[140]
Puducherry, South of Chennai Sewage Treatment Plant 17.8 MLD	15748 tCO_2eq/yr	4650 tCO_2eq/yr	718 tCO_2eq/yr	India	[141]
Nigerian Greenhouse Inventory	2015-14635.4 $GgCO_2eq$ 2016-15025.0 $GgCO_2eq$ 2017-1533.18 $GgCO_2eq$	-	2015-5842.2 $GgCO_2eq$ 2016-5997.8 $GgCO_2eq$ 2017-5997.8 $GgCO_2eq$	Nigeria	[142]
Swedish WWTP 805,000 m^3/yr (treated wastewater); 147,300,000 PE	*28.5-33.5 kg CH_4 h^{-1}	-	*4.0-6.4 kg h^{-1}	Sweden	[143]
Ain Taoujdate WWTP				Morocco	[144]
2013-27,589 PE	7141.68 $KgCO_2$/y	-	1417.83 $KgCO_2$/y		
2018-30,807 PE	7920.05 $KgCO_2$/y	-	1662.36 $KgCO_2$/y		
2019-31,465 PE	4927.104 $KgCO_2$/y	-	1697.87 $KgCO_2$/y		

MLD- million liters per day, PE- population equivalent

crease in rainfall can cause possible aquifer contamination, due to insufficient water to constantly recharge aquifers and this can pose potential health and environmental risks [147]. A summary of the impact of climate change as it affects the different areas of wastewater management is presented in Table 5. To set up robust wastewater treatment facilities, engineers should work with climatologists and regulating agencies to determine and predict climate patterns and or the impact of climatic events. This will go a long way in alleviating problems experienced in the operations of the wastewater treatment plants.

Table 5. Impact of climate change on different components of wastewater system [148].

Components of waste water system	Climate factors				
	Increased rainfall	Decrease in rainfall/drought	Rise in sea-level	Temperature	Wind
Wastewater conveyance	-increased overflows, blockages and breakages	-corrosion resulting in increased waste concentration	-breaking of pipes due to increased groundwater level -corrosion -erosion causing damage to infrastructure	-increased odors	-increased blockages, damages and breakages related to rainfall events and or storms
Pump stations	-increased overflows and blockages	-corrosion resulting in increased waste concentration	-corrosion -erosion -flooding resulting in a reduction in the service zone of the pump station	-blockages caused by user behavior changes in hot weather (e.g., flushing of wet wipes)	-increased blockages, damages and breakages related to rainfall events and or storms
WWTP in general	-increased inflows leading to recurrent bypassing -power outages associated to storm events	-increased concentration of influent risking higher toxicity levels	-flooding and damage of infrastructure -elevated groundwater table impeding sludge management dewatering	-the performance of biological systems, oxidation ponds and sludge management are affected by temperature -odors	-increased blockages, damages and breakages related to rainfall events and or storms
On-site wastewater	-waterlogged soils affect soakage capability -ecological changes to soakage fields	-ecological changes to soakage fields	-waterlogged soils affect soakage capability -ecological changes to soakage fields	-performance varies with temperature -odors	

8. CONCLUSION

The importance of wastewater treatment cannot be overemphasized. However, it is important to recognize that the processes involved in the treatment of wastewater are significant sources of GHGs. The impact of these emissions on the environment is palpable as the effect of climate change are now obvious. Apart from optimizing processes and plant designs to minimize GHG emission various methods have been implemented to curb their release. Microbial electrosynthesis, microalgae cultivation, microbial carbon capture and direct carbon capture are recent technologies for mitigating carbon dioxide emissions. Methane can be captured and serve as natural gas and carbon source for methanotrophs and in denitrification process in wastewater treatment. The use of algal technologies has been suggested as a solution for nitrous oxide emission while membrane aerated bioreactors have been reported to minimize nitrous oxide emission in a full scale WWTP. The use of renewable energy will aid in minimizing emissions from energy use as well as save energy. Implementing these solutions and monitoring the scope of emissions will serve in combating environmental problems caused by emission of GHGs and mitigate impact on climate change and will also ameliorate difficulties faced in the management of wastewater in wastewater treatment plants. Continuous research is however, needed to keep abreast the relationship between wastewater treatment, greenhouse gases and climate change and to develop more effective solutions to mitigate future problems.

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