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Effect of climate change in WWTPs with a focus on MBR infrastructure

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ABSTRACT

Climate change is expected to be one of the main challenges for urban wastewater systems in the next decades, and it is estimated that it will have a dual effect on wastewater treatment plants (WWTPs). The processes occurring in a WWTP are affected by climate change; more extreme weather events and earlier snowmelt runoff will lead to more untreated sewer overflows, increased flooding, etc. On the other hand, wastewater treatment contribute to climate change itself, as during wastewater treatment greenhouse gases, including carbon dioxide (CO_2) from aerobic (oxidation processes), methane (CH_4) from anaerobic processes and nitrous oxide (N_2O) associated with nitrification/denitrification processes, can be emitted to the atmosphere. MBR is currently considered a rather mature technology (not innovative) with several full-scale applications; N_2O is also produced during the nitritation process (i.e. ammonium oxidation to nitrite). Moreover, the microbial communities developed in MBRs are exposed to completely different conditions depending on the season of the year (spring, summer and autumn). The various problems associated with climate change and MBRs/WWTP operation and the solutions that can be applied to deal with them are summarized in this paper.

Keywords: Climate change; Wastewater treatment; MBRs

1. Introduction

1.1. Wastewater treatment plants

Each particular wastewater treatment plant (WWTP) may be subjected to various operation conditions and restrictions i.e. variable flow of incoming wastewater, quality of sewage, permitted levels of effluent and other local guidelines. These differences may have a significant impact on the type of process used for treatment.

A conventional municipal WWTP includes the following main stages of processing:

1. *Pretreatment*: solids removal with relatively large diameters (e.g. >1 mm);
2. *Primary treatment*: removal of solids that settle relatively easily aiming to reduce the concentration of particulates;
3. *Secondary treatment*: removal of biodegradable organic substances by biological processes (micro-organisms consume the organic content under aerobic or anaerobic conditions);

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(4) *Tertiary Treatment and Disinfection*: treatment of the secondary effluent by filters, membranes etc. Destruction of pathogens micro-organisms; and
(5) *Sludge disposal*: in landfills, by composting or by incineration.

In the conventional municipal systems, wastewater after primary treatment, i.e. after suspended solids removal, is treated by the activated sludge process (Fig. 1) that is carried out in an aeration tank followed by a secondary clarifier. Activated sludge is the most common and oldest biological process used for the treatment of municipal and industrial wastewater.

1.2. Membrane bioreactor systems (MBRs)

MBRs are becoming more common as WWTPs are required to meet increasingly stringent effluent limits and in some cases, reuse requirements in smaller footprints. The unique feature of MBRs is that instead of secondary clarification (Fig. 2), they use membrane treatment, either as vacuum-driven systems immersed in a biological reactor or pressure-driven membrane systems located external to the bioreactor, for solids separation. Membranes are typically configured as hollow tube fibres or flat panels and have pore sizes ranging from 0.1 to 0.4 μm. The membrane biological reactor configuration has proven to be optimal for the treatment of a large number of industrial wastewaters, especially when treatment efficiency is an important consideration [2].

1.3. Climate events

Climate change is expected to be one of the main challenges for urban wastewater systems in the next decades. Due to increasing concentrations of greenhouse gases (GHG) in our atmosphere, temperatures are expected to rise between 2 and 5˚C globally by 2050 (a reference is needed here).

Climate change is affecting the hydrologic cycle in various ways. Precipitation patterns are changing, permanent snow covers and ice sheets are melting, and atmospheric water vapor and evaporation is increasing. Evaporation is increasing as a result of increasing land and water surface temperatures and with increased temperature the water holding capacity of the atmosphere is increasing. As atmospheric moisture content directly affects precipitation, stronger rainfall events are expected with climate change [3].

The wastewater industry is beginning to address the challenges posed by climate change, including regulatory burdens, pressure to reduce emissions and the challenge of adapting to a changing climate [4].

1.4. Greenhouse gases

Gases that trap heat in the atmosphere are called GHG. Carbon dioxide (CO_2) is the principal GHG (Fig. 3), but other gases can have the same heat-trapping effect. Some of these other GHG, however, have a much stronger greenhouse, or heat-trapping effect than CO_2. For example, methane is 21 times more potent GHG than CO_2.

Different GHGs have different atmospheric life times, and therefore actions to reduce emissions will take time to effect reductions of gases in the atmosphere. The principal, human-generated GHG that enter the atmosphere is summarized Table 1.

2. WWT affected by climate change

2.1. Associated problems

2.1.1. Climate events

On a consideration of the wastewater infrastructure and baseline climate data, the following climate factors were identified as being particularly significant [8]:

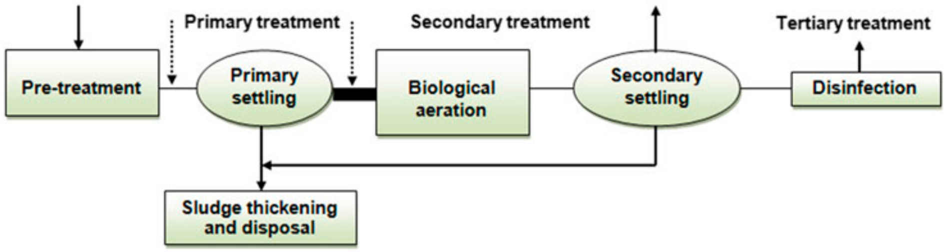

Fig. 1. Conceptual diagram of a typical activated sludge process.

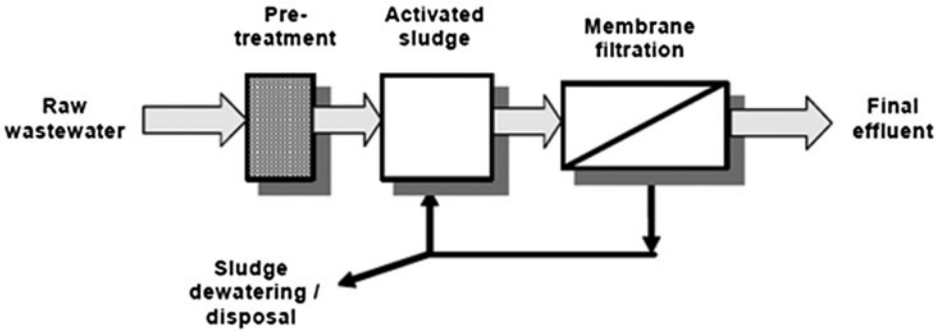

Fig. 2. Conceptual diagram of a membrane bioreactor system [1].

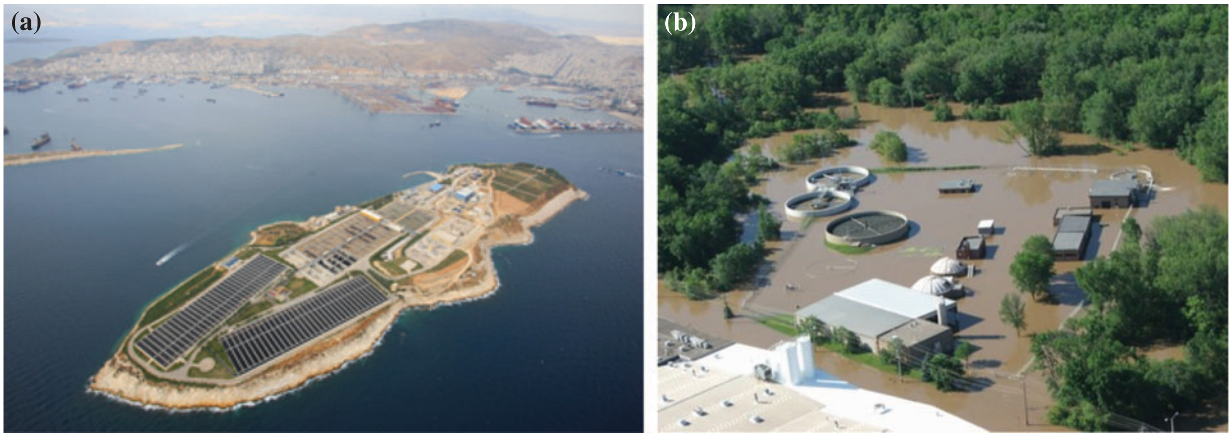

Fig. 3. (a) Psittalia WWTP, Athens, Greece [5], (b) flooded WWTP. City of Reedsburg, Wisconsin, USA. June 10, 2008 [6].

Table 1
The human-generated GHG that enter the atmosphere [7]

GHGs	Characteristics
Carbon dioxide (CO_2)	Enters the atmosphere through the burning of fossil fuels (oil, natural gas and coal), production and transport of coal, natural gas and oil
Methane (CH_4)	Results from livestock and other agricultural practices and by the decay of organic waste in municipal solid waste landfills and anaerobic WWTPs. CH_4 is a greenhouse gas approximately 21 times more potent than CO_2 and has an atmospheric lifespan of roughly 12 years
Nitrous oxide (N_2O)	Is emitted during agricultural and industrial activities, as well as during the combustion of fossil fuels and solid waste. Nitrous oxide is also emitted from WWTPs during NDN. N_2O is 298 times more potent as a greenhouse gas than CO_2 and has an atmospheric lifespan of 120 years
Fluorinated gases	Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) are synthetic, powerful GHG that are emitted from a variety of industrial processes. These gases are typically emitted in smaller quantities, but because they are potent GHG, they are sometimes referred to as High Global Warming Potential gases (High GWP gases). HFCs are 140–11.700 times more potent than CO_2 and have atmospheric life spans of 1–260 years. Most commercially used HFCs remain in the atmosphere less than 15 years. PFCs are 6.500–9.200 times more potent than CO_2 and have an atmospheric lifespan of several thousand years. Sulphur hexafluoride is 23.900 times a more potent greenhouse gas than CO_2 and is extremely long lived with very few sinks

1. Rainfall (intensity–frequency relationships, annual and seasonal totals). Wastewater infrastructure is affected by rainfall storm events and, to a lesser degree, by the total annual rainfall;
2. Sea level elevation;
3. storm surge;
4. Rain on snow events (another flood generation mechanism);
5. Extreme temperatures (low and high);
6. Drough conditions;
7. Snowfall (predictions of increasing temperatures in the coming years during all months lead to expectations of decreasing snowfall trends);
8. Wind speed (extremes and gusts);
9. Frost (freeze-thaw cycles); and
10. Ice.

2.1.2. Temperature

Biological wastewater treatment (WWT) is very much influenced by climate. Temperature plays a decisive role in some treatment processes, especially the natural-based and non-mechanized ones. *Warm temperatures* decrease land requirements, enhance conversion processes, increase removal efficiencies and make the utilization of some treatment processes feasible. Some treatment processes, such as anaerobic reactors, may be utilized for diluted wastewater, such as domestic sewage, only in warm climate areas. Other processes, such as stabilization ponds, may be applied in lower temperature regions, but require much larger areas and are subject to a decrease in performance during winter. Activated sludge and aerobic biofilm reactors, are less dependent on temperature, as a result of the higher technological input and mechanization level [9].

2.1.3. Rising sea levels/storms

With the onset of rising sea levels and river flooding, many water utilities have become threatened by flooding which can have multiple negative consequences. Flooded wastewater facilities have the potential to release untreated waste into ecosystems, causing significant damage to the environment and human health. If the wastewater facility suffers structural damage it may have to release untreated waste for an extended period of time until the facility can be repaired. Flood damage would be costly to municipalities both in terms of financial loss and in terms of threats to public health. Careful advance planning to prepare for the consequences of sea level rise and flooding is essential [10].

Particularly, the effects of increased flooding and rising sea levels on WWTP are:

1. The expected increase in the frequency of storm events can cause flooding, which can be harmful to infrastructure when WWTPs are built in coastal areas or in areas affected by river floods (Fig. 4(a));
2. Strong waves during storms can be very damaging to effluent pipes, creating more maintenance needs;
3. Sea level are expected to rise in some areas by 2050 endangering the location of many WWTP;
4. Rising downstream water levels may make pumping effluent a requirement and increasing the facility’s energy needs [12].

Increased frequency and intensity of rainfall is one of the most immediate effects of global warming that is already apparent in stream flow records from the last several decades. The expectation is that more severe storms will produce more severe flooding. This will inevitably result in additional water pollution from a large variety of sources. An increase in volumes of wastewater to be treated will affect WWT, storage and conveyance systems [13].

Increased tropical storm intensities will have negative effects on water resources (Fig. 3(b)). More intense tropical storms can damage infrastructure, due to increased flooding, which can overwhelm water infrastructure, and cause pollutants to directly enter waterways and contaminate water supplies [6].

2.1.4. Impacts on water pollution

According to the EPA, for the most part, WWTPs and combined sewer overflow control programmes have been designed on the basis of the historic hydrologic record, taking no account of prospective changes in flow conditions due to climate change. As a result, it is conceivable that water suppliers will face a continually increased influent challenge from sewage overflows, producing high concentrations of *Giardia*, *Cryptosporidium* and coliforms [13].

In the future, wastewater reuse and desalination will possibly become important sources of water supply in semi-arid and arid regions. An increase in WWT in both developed and developing countries is expected in the future, but point source discharges of nutrients, heavy metals and organic substances are likely to increase in developing countries. In addition,

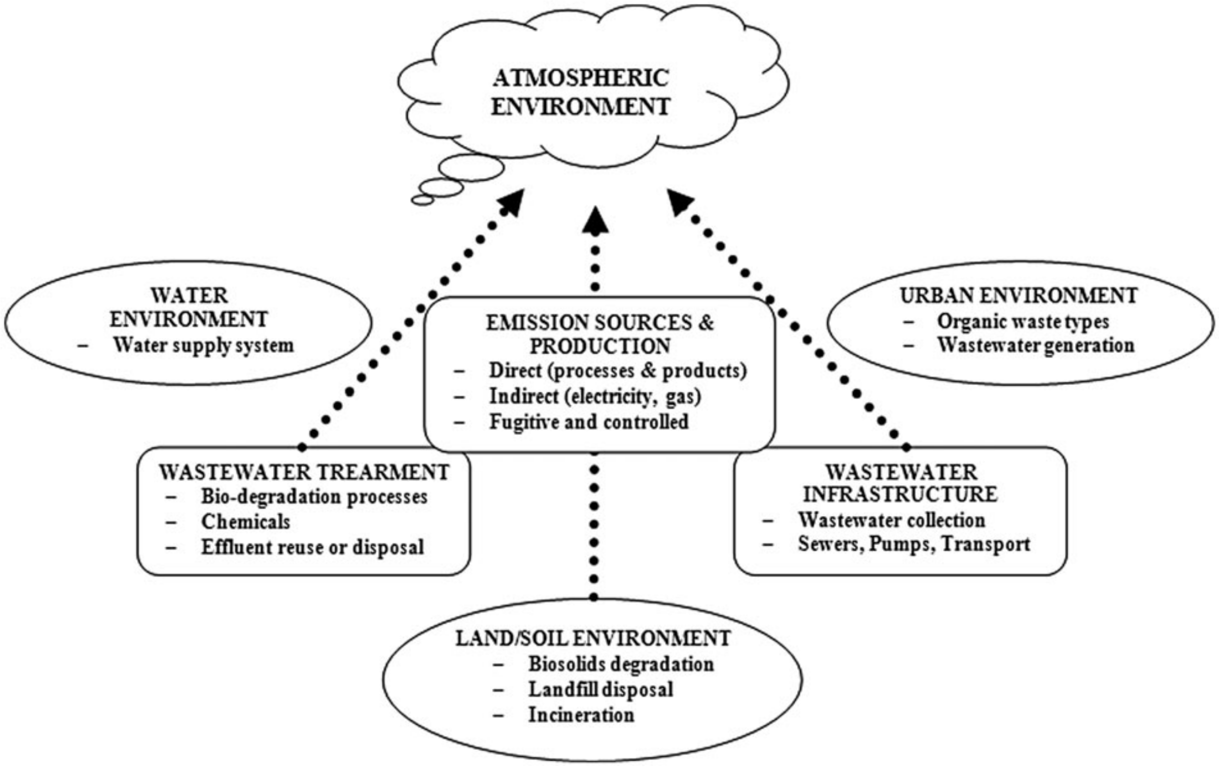

Fig. 4. GHG emission assessment framework from wastewater [11].

more frequent heavy rainfall events will overload the capacity of sewer systems and water and WWTPs. An increased occurrence of low flows will lead to decreased contaminant dilution capacity meaning higher pollutant concentrations, including pathogens. In areas with overall decreased runoff (e.g. in many semi-arid areas), water quality will be even worse [14].

2.1.5. *Affected processes in a WWTP*

The main processes in a WWTP, affected by the climate change, are listed below:

(1) Sedimentation
   (a) Warm wastewater increases the bacterial reaction rate, which reduces the density of settled sludge;
   (b) Inflow wastewater will be more dense so experiments will need to be done;
(2) Biological aeration of warm wastewater
   (a) Increased BOD;
   (b) Activated sludge aeration systems operating at high temperatures support nitrification;
(3) Processing of waste sludge
   (a) Waste activated sludge must be thickened for efficient and effective digestion;
(4) Stabilization ponds
   (a) Pros: reliable treatment, and minimal operation/maintenance;
   (b) Cons: land demand, infrastructure, sealed bottoms to prevent groundwater contamination, potential emission of foul odours;
(5) Chlorination [13].

2.2. *MBRs affected by climate change*

In biological WWT, the removal of organic matter relies on the activity of a mixed community of heterotrophic micro-organisms. In order to control the efficiency of the WWT processes, it is important to recognize the variables that regulate microbial hydrolases. The activity of these enzymes in WWT plants is controlled by diverse microbial mechanisms which respond to changes in the variables influencing the system, such as the availability of nutrients, electron acceptor conditions, pH or seasonal temperature.

The adaptation of the hydrolytic activities of the activated sludge microbial community to changes in variables influencing a full-scale MBR system is examined by researchers in three different seasons of the year (spring, summer and autumn). Daily medium internal temperature measured in the sludge of the MBR system. Concentration of total suspended solids, concentration of volatile suspended solids, concentration of total nitrogen, total chemical oxygen demand (COD) and total biological oxygen demand at five days (BOD_5) were analyzed daily in influent and effluent (permeate) water.

Significant differences ($p < 0.1$) were found depending on the season. Important fluctuations in the enzyme activities were recorded for all tested hydrolases, particularly during the spring. The highest quantitative variation between seasons was observed for a-glucosidase, which was higher in the spring compared to the summer and autumn [15].

2.3. Applied solutions

Growing evidence indicates that the water sector will not only be affected by climate change, but that it will deliver many of its impacts through floods, droughts or extreme rainfall events. Water resources will change in both quantity and quality, and water, storm water and wastewater facilities' infrastructure will face greater risk of damage caused by storms, floods and droughts. The effect of the climate change will manifest from difficulties in operations to disrupted services and increased cost of the water and wastewater services. Governments, urban planners and water managers must therefore re-examine development processes for municipal water and wastewater services, and are adapting strategies to incorporate climate change into infrastructure design, capital investment projects, service provision planning, and operation and maintenance.

Wastewater systems built on historical design parameters, such as max/min flow levels or storm water capacity, will become obsolete and reconstruction rather than rehabilitation may become necessary. With reduced flow in receiving water, meeting the ambient water standards after dilution of WWTPs' effluent may become increasingly difficult and can result in a need for increased treatment standards [16].

2.3.1. Adaptive capacity

The degree to which a municipality is able to deal with the impacts of climate change is often referred to as adaptive capacity. According to the Intergovernmental Panel on Climate Change (a global scientific body set up by the World Meteorological Organization and the United Nations Environment Program), Adaption is defined as "the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" [17].

2.3.2. Assessment tool

To consider the effects of a facility flooding on the surrounding community, an impact assessment tool was created. Suitable tools were developed in wastewater facilities. The crucial factor that was considered for wastewater facilities was the ratio between the average flow rate and the design flow rate of the plant. This ratio measures how close to the maximum capacity a WWT facility operates. A facility which operates close to the maximum capacity will be less able to handle an increase in inflow, which may be caused by a storm or flood, than a facility which does not operate close to the maximum capacity. Facilities which have an average flow rate of up to 50% of their design capacities were rated as low impact. Facilities with an average flow rate above 50% and up to 70% of their design capacities were rated as medium impact. Facilities with an average flow rate above 70% of their design capacities were rated as high impact [10].

2.3.3. Monitoring of WWTPs

Over the last decade, continuous and long-term monitoring of urban wastewater infrastructure has increasingly been applied due to the availability of reliable and affordable sensors, data communication and data handling capacity. This has resulted in the availability of large data-sets, describing the performance of the wastewater infrastructure in long-time series. Combining these monitoring data with meteorological data, it is possible to study the impact of anticipated climate changes by identifying periods in time in the data-set that resemble to weather conditions which are representative of expected future climatic situations. This "data mining" could result in identifying relevant processes to be taken into account in a model-based analysis of climate change impacts [18]. Wastewater operations monitoring provide changes in volumes and composition of wastewater, brakes and clogs in wastewater collection network, adequacy of existing technology to composition of wastewater and WWT effluent and sludge [16].

2.3.4. Vulnerability analysis

Water utilities across the country have initiated some research efforts to investigate their vulnerability to climate change processes. Such efforts attempt to obtain a better analytical assessment of the possibility that current water resource development and facility plans could be disrupted by near-term (20–50 year) manifestations of climate change processes. This initial centre on vulnerability is a good means of identifying prior issues related to climate change and lays the foundation for follow-up actions. Two alternative approaches to vulnerability analysis have been articulated: "top-down" and "bottom-up." Many initial vulnerability analyses have been related to water resource and facilities planning. However, direct impacts on water utility facilities from flooding due to more intense rainfall activity or sea level rise are other obvious priorities to be analyzed.

Some of these efforts have employed climate models (referred to as GCMs—General Circulation Models) to attempt to build climate change forecasting into the front end of water supply planning. This has been labelled the "top down" approach to vulnerability analysis. The major drawback of this approach lies in the current level of analytical resolution of the GCMs. In contrast, a "bottom-up" approach to vulnerability analysis has also been articulated as a recommended path for utilities to follow in investigating impacts of climate change. The central idea of this approach is that utilities can work with their own water resources planning models to assess the vulnerability of their 20–50 year supply plans to climate change. The "bottom-up" analysis enables a utility to test the robustness of current plans to upsets from changes in key climate-related variables limited to one or several models and without trying to undertake new climate modelling work [13].

2.3.5. Membrane treatment processes

Many water suppliers in overconstrained settings have also turned to energy-intensive membrane treatment processes to enable desalination of saline water sources and reuse of highly treated wastewater effluent. These processes make it possible to overcome any deterioration in the reliability of normal sources of supply by making it possible to meet part of the demand from sources that will be abundant under most climate change scenarios (i.e. yields from water reuse and desalt supply options are drought resistant). If these technologies fill a gap or hide a vulnerability produced by climate change processes, in a way that enables a broader scope for optimization across the entire portfolio, they can play a critical role in improving the overall optimization [13]. For optimization purposes, a lab-scale pilot plant which consists of a sequence of four tanks: (1) waste; (2) biological treatment; (3) separation activated sludge membranes; (4) treated waste, with fully automatic operation, has been constructed and tested (the automatic operation of the pilot plant is achieved by means of programmable logic controller—PLC) by Gkotsis et al. [19].

3. Climate change affected by WWT

3.1. Associated problems

The quantity of wastewater collected and treated is increasing in many countries in order to maintain and improve potable water quality, as well for other public health and environmental protection benefits. Concurrently, GHG emissions from wastewater will decrease relative to future increases in wastewater collection and treatment [14].

The study of gaseous emission, climate change and air pollution is committed to physicochemical identification, inventories, measurement and assessment methods as well as to quantitative study of the actual anthropogenic sources and its direct contributions. The causes provoked by human activities include:

1. Emissions from wastewater discharges;
2. Sewage collection and transportation;
3. WWTPs; and
4. Associated activities.

The level of uncertainty in the wastewater industry's "carbon profile" is unacceptable in the emerging business environment of carbon pricing, and managerial commitments to "zero carbon emission". Methane and nitrous oxide emissions in particular have much higher global warming potentials than CO_2 [20].

3.2. GHG emissions from WWT

During the WWT, GHG including CO_2 from aerobic (oxidation processes), methane (CH_4) from anaerobic processes and nitrous oxide (N_2O) associated with nitrification/denitrification (NDN) processes, as an intermediate product, can be emitted to the atmosphere. Table 2 displays the expected GHG emissions that occur during the processes in a WWTP.

Municipal sewage treatment plants play an important role in the abatement of water pollution, but they also produce a large amount of gaseous emissions to atmosphere. The discharge of large volumes of fugi-

Table 2
Expected direct GHG emissions for WWT plant processes [21]

Process	Expected direct GHG emissions
Primary	None
Secondary	CH_4, from anaerobic treatment processes (i.e. lagoons)
Advanced	N_2O, from NDN process
Solids handling	CH_4, from sludge handling such as digestion or from incomplete combustion of digester gas and emissions from offsite operations
Effluent discharge	N_2O, from denitrification of nitrogen species originating from wastewater effluent in receiving water

tive gases that contains low levels of chemical constituents may still lead to an excessive contribution to air pollution. Most centralized WWT methods consist of a combination of biological processes (activated sludge reactors, trickling filters, anaerobic digesters, etc.) that promote biodegradation of organic matters by micro-organism and production of anthropogenic CH_4, and N_2O gaseous emissions. Methane (CH_4) production is directly resulting from anaerobic decomposition of the organic matter present in sewers. The methanogenesis or CH_4 production rate depends primarily on the concentration of the degradable organic material in wastewater measured by biochemical oxygen demand (BOD_5) and COD. The main environmental factors which influence methane production include; retention time, pH, temperature, presence of sulphate reducing bacteria and methanogens [11,22].

Nitrous Oxide (N_2O) and nitric oxide (NO) production is associated with breakdown of nitrogen components that are common in wastewater, e.g. protein and urea. Biological nutrient removal processes have the ability to transform the ammonia and organic nitrogen compounds into nitrogen gas, which can be released to the earth's atmosphere. The two-phase process involves nitrifying bacteria (*Nitrosomonas*) that oxidize ammonia to create nitrate (aerobic phase), while denitrifying bacteria reduce nitrate, turning it into nitrogen gas, which is then released to the atmosphere (anoxic phase). N_2O and NO can be released during both of these processes; however, it is mainly associated with denitrification. Aerobic treatment process produces relatively small emissions, whereas anaerobic processes emission can increase by 50–80% [11,23].

CO_2 production is attributed to two main factors; the treatment process and the electricity consumption. During anaerobic process, the BOD_5 of wastewater is either incorporated into biomass or it is converted to CO_2 and CH_4. A fraction of biomass is further converted to CO_2 and CH_4 via endogenous respiration. Short cycle or natural sources of atmospheric CO_2 which cycle from plants to animals and to humans as part of the natural carbon cycle and food chain do not contribute to global warming. Photosynthesis produced short-cycle CO_2, removes an equal mass of CO_2 from the atmosphere that returns during respiration or WWT. Digestion processes, either aerobic or anaerobic, emit also only short-cycle CO_2 [11].

The hydrogen sulphide (H_2S) gas evolves from the anaerobic decomposition of organic matter or from the reduction of mineral sulphites and sulphates. H_2S gas mixed with the sewage gases ($CH_4 + CO_2$) is highly corrosive to sewer pipelines, manholes, concrete junction chambers, mechanical and electrical equipment [11,22].

Volatile organic compounds (VOCs) emission occurs during entire wastewater cycle. A significant fraction of VOCs is released to atmosphere by gas–liquid mass transfer. VOCs production during wastewater transportation in sewers occurs during turbulent flow and air exchange between ambient atmosphere and wastewater. The transfer rate of emission is affected by physicochemical properties of chemicals, fluid and flow characteristics. There is a growing concern that several VOCs that are present in wastewaters, especially industrial effluents, find their way to the atmosphere. In particular VOCs such as benzene, chloroform, ethyl benzene, toluene, *m*-xylene and *o*-xylene are found in refinery and petrochemical wastewaters in significant amounts as well as in many municipal wastewaters [11,24,25].

3.3. Climate change affected by MBRs

The major fugitive GHG emissions are sourced from the anoxic/aerobic zones in the MBR systems (especially of decentralized systems). When the MBR is coupled with an upstream primary holding tank, the susceptibility to various shock loads is enhanced owing to its buffering capacity. The membrane bioreactor (MBR) system is relatively robust to hydraulic shock loads with tolerance up to 1.5 times of the design dry weather daily flow. However, the stability of nitrification process in MBR is significantly affected when the total nitrogen load in the influent increased by 30% while maintaining the constant inlet wastewater flow rate. By a mass balance approach to estimate the fugitive GHG emissions is concluded that electrical energy consumption data alone could substantially underestimate the overall GHG footprints for the MBR systems [26].

It was found that the aerobic tank did not emit any fugitive gases, apart from a very small amount of CH_4 released after surface watering. This small amount of CH_4 may have been released from sludge deposited via water spray from the anoxic tank. The anoxic tank emitted highly variable amounts of both CH_4 and N_2O during all three operational conditions, with the highest level of CH_4 (53 g CO_2-e/m^2/d) being emitted after a 2 h site shutdown period, whilst the most N_2O (17 g CO_2-e/m^2/d) was emitted when the MBR system was working under normal conditions [27].

4. Applied solutions

4.1. General

As climate change is a major concern, alternatives should reduce GHG emissions, making anaerobic treatment a more attractive component of novel approaches to treatment processes.

4.2. Vulnerability and climate assessment

The definition of assessment framework, proposed by Listowski et al. in 2011 [11] for gaseous emissions from urban wastewater system (Fig. 4), appears necessary to the development of future adaptation strategies and knowledge to manage emissions from wastewater cycle. It should be developed to interact with the adaptive responses that could address emission sources, infrastructure, the pathways for gaseous emissions and its concentrations, mitigation capabilities and technologies. The main tasks in assessment framework incorporate several areas including:

(1) Understanding the emission generation processes (spatial, temporal, physical, biochemical) with the key motivation issues including the pathways for gaseous emissions and concentrations;
(2) Identifying the appropriate and reliable parameters as a basis for the adaptation of the strongly variable combined wastewater flow to the actual treatment capacity;
(3) Establishing the credible methods of obtaining data and information from defined emission sources;
(4) Quantifying and predicting the gaseous emissions. Amongst the broad diversity of wastewater sector the analysis of gaseous emissions could be assessed in two essential emission categories:
    (a) Direct emission linked with wastewater sources and activities that promote fugitive gaseous emission related to physical and biochemical processes that are characteristic to wastewater and its by-products during the wastewater cycle;
    (b) Indirect emission—energy use associated with the wastewater transportation, pumping, various treatment processes, effluent disposal, residuals management, etc.

The main factor in this regard is the use of biological WWT, aerobic or anaerobic treatment technology, sludge processing and also the electricity used. While assessment of emission related to energy consumption (CO_2 equivalent) is relatively straight forward, quantifying direct fugitive emissions (“fugitive” emissions of nitrous oxide and methane from WWTP operations since both of these gases are major greenhouse contributors) from wastewater systems is an area of uncertainty for the industry, with less developed and less reliable methodologies. The diffused emissions include substances such as: CH_4, CO_2, VOCs, NO_x, CO, Mercury, Cadmium and Lead, hydrogen sulphide (H_2S), ammonia (NH_3), and sulphur dioxide (SO_2), which have adverse affect on air quality, environment and public health [11].

4.3. Methane as a fuel

The methane emission related to the anaerobic digestion of primary and secondary sludge counts for about three quarters with respect to the WWTPs overall methane emission and causes a slightly larger GHG footprint than the CO_2 emission that is avoided by using the resulting biogas for energy generation. Methane emissions can be significantly reduced by better handling of the ventilation air of sludge handling facilities; one way to valorize the residual methane that is produced in the buffer tank is to use the ventilation air from the buffer tank as combustion air in the gas engines of the cogeneration plant. The methane concentration in the ventilation air could of course be increased using less fresh air for ventilation. This would result in less diluted methane streams, but then the ventilation system should be adapted to handle methane concentrations that exceed the lower explosive limit of methane in air, which is 4.4% [28].

Recovering the energy to provide heat and electricity for WWTPs process can offset significant fossil fuel-related GHG emissions. In general, intuitively sustainable practices for biosolids (energy recovery and recycling nutrients and organic matter) reduce

GHG emissions. Besides, the methane that is emitted to the atmosphere not only contributes to the GHG footprint of a WWTP, it also implies a waste of energy since the methane emitted from the unit processes that are related to the anaerobic digestion (7–2% of the produced methane) could potentially have been used as a fuel for the cogeneration plant. Although biogas production from waste sludge may be a sustainable technology from an energy point of view, it has in this case no benefits over fossil fuel-derived energy regarding GHG emissions. Nonetheless, it should be emphasized that the emission of methane is not intrinsic for anaerobic digestion, but that a better design and good housekeeping may lead to a drastic mitigation of the emission [28].

4.4. MBRs

Interestingly, the lowest emissions of both CH_4 and N_2O were measured to be over the anoxic tank after cleaning and surface watering was performed. This reduction may have been due to the sprayed and deposited water forming a microlayer membrane or a thicker film as a protective barrier over the sewage surface, which may have prevented a large proportion of gases from being released into the atmosphere. During all operational conditions, CO_2 emissions were also found to be released from both the aerobic and anoxic sections of the MBR system. However, this CO_2 is widely regarded as being a short-term biogenic gas readily produced by the breakdown of organic matter. As it is not generated by fossil fuel burning and does not measurably contribute to the greenhouse effect, it is not included in the total GHG emissions footprint [27].

5. Conclusions

It is estimated that Climate change has a dual action on WWTPs. The processes occurring in a WWTP are subsequently affected by climate change; more extreme weather events and earlier snowmelt runoff will lead to more untreated sewer overflows, increased flooding, etc.

The limitation of climate changes' effects on WWT processes can be achieved by applying an impact assessment tool, by monitoring of WWTPs and using vulnerability as a good means of identifying a utility's priority issues relating to climate change.

In the other hand, we have the WWT contribution to climate change itself, as during the WWT, GHG including CO_2 from aerobic (oxidation processes), methane (CH_4) from anaerobic processes (3–19%) and nitrous oxide (N_2O) (3%) associated with NDN processes, as an intermediate product, can be emitted to the atmosphere.

The development of future adaptation strategies and knowledge to manage emissions from wastewater cycle appears necessary and the Vulnerability climate assessment should be developed to interact with the adaptive responses that could address emission sources. Furthermore, recovering the energy to provide heat and electricity for WWTPs process using the resulting biogas from the anaerobic digestion of sludge can offset significant fossil fuel-related GHG emissions (CH_4 etc.).

During MBRs operation, the major GHG emissions (mainly N_2O and CH_4) are sourced from the anoxic/aerobic zones of the MBR systems (especially of decentralized/small systems). In the other hand, the microbial communities developed in MBR-based treatments are exposed to completely different conditions depending on the season of the year (spring, summer and autumn).

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