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Prediction of Greenhouse Gas Emissions from Wastewater Treatment and Biogas Production in Tunisia

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Abstract

Tunisia, a country located in North Africa, is one of the MENA region countries suffering from several problems due to climate change, such as water stress, need for electricity, and waste and wastewater management. Wastewater treatment with biogas and electricity production represents a promising energy option for Tunisia, especially with the important quantities of sludge extracted from wastewater and disposed of in landfills. It is important, though, to know the number and sources of emissions that can be generated with biogas in order to ensure a good implementation of it. This study quantifies the emissions from different processes in a wastewater treatment plant with biogas production using adequate estimation methods for this case. Results showed that total annual emissions from wastewater treatment and biogas production on a national level could reach 515.25 kt CO_{2eq}. Methane emissions from anaerobic digestion were the highest source of emissions. Carbon dioxide emissions from activated sludge were also significant. The other sources of emissions were nitrous oxides from the whole plant, electricity consumption, cogeneration, and carbon dioxide emissions from anaerobic digestion. This work represents a first attempt to picture the future wastewater treatment scenario that considers emissions when installing biogas production technologies in Tunisia, which can support emission management and, therefore, reduce the resulting environmental impact.

Keywords: biogas, climate change, GHG emissions; Tunisia; wastewater treatment

1. Introduction

The world currently faces the challenge of satisfying the increasing needs of the growing population for food, water, and energy and trying to protect the life on earth by controlling the human activities that harm the environment (Golam et al., 2015; Im Sangjun et al., 2016). One of the problems caused by human activity is climate change and global warming, which cause problems such as the increasing risk of water scarcity in many countries (Gosling & Arnell, 2016; Seckler et al., 1999). The most endangered region from water scarcity currently is the Middle East-North Africa (MENA) region, and it is the most exposed and vulnerable to the impacts of climate change (Iglesias et al., 2007; Namdar et al., 2021; Waha et al., 2017). Tunisia is one of the MENA countries located in northern Africa and is characterized as an arid country currently in danger of water stress (Norris, 2020).

On the other hand, waste management and wastewater treatment also represent one of the most significant issues in the MENA region and Tunisia, combined with the lack of effective waste-to-energy strategies (Abumoghli, 2020). The treatment and valorization of wastewater and sludge can help reduce the intensity of the water stress problem by using the treated water for agricultural use. Also, the generated sludge can be exploited to produce two types of energy- electricity and heat, which can reduce the wastewater treatment plants (WWTPs) needs for electricity from fossil fuels and, therefore, contribute to solving the ongoing electricity demand requirements (Armaroli & Balzani, 2011; Esteves et al., 2015). Hence, producing electricity from biomass such as sludge is a favorable solution for the region, especially Tunisia, which is experiencing increasing energy demand due to the growing population (Aghahosseini et al., n.d.).

The government of Tunisia has been encouraging water reuse since the mid-1960s. Its plans also include the installation of anaerobic digesters and cogeneration units in 12 WWTPs in different locations of the country to produce biogas from sludge and generate electricity and heat ("569 Case: Wastewater And Biosolids For Fruit

Trees Wastewater And Biosolids For Fruit Trees (Tunisia)"). In 2017, Tunisia had a connection rate to WWTPs of 88%, of which 99% is treated, equivalent to a daily flow of 786 000 m^3. Despite those efforts, there are still challenges to making wastewater treatment and valorization management more successful. For instance, out of 123 WWTPs in Tunisia, only 9 dry a small part of the extracted sludge (equivalent to 214 000 m^3 per year) from the treatment process and provide it for agricultural use as fertilizer. The rest of the sludge is disposed of in landfills ("Onas Annual_Report_2019", 2019).

On the other hand, biogas technology has been explored in Tunisia since the 1980s, but this use was limited to only small-scale digesters used on farms ("The application of biogas technology to the treatment of industrial waste in tunisia", 1994). Although anaerobic digesters were introduced to three WWTPs, biogas production has stopped in two of them due to budget limitations, lack of maintenance, and administrative challenges ("Etude sur le développement de la méthanisation industrielle", 2010). A preliminary study about biogas in Tunisia predicted that the amount of sludge produced in 2030 would be 151.131 thousand tons, equivalent to 90 798.127 million m^3 of biogas from which 544.78 GWh of electricity can be generated and can cover 3% of Tunisia's electricity needs, which makes biogas from wastewater treatment a promising technology (El Houda et al., 2020; "Etude sur le développement de la méthanisation industrielle", 2010). One of the current government's strategies to encourage biogas production is the National Energy Management Fund (FNME)'s contribution with 40% of the initial installation cost for biogas production and 20% of the initial installation cost for biogas production to generate electricity ("Convention cadre des nations unies sur les changements climatiques premier rapport biennal de la tunisie", 2014).

Despite the anticipated benefits of wastewater treatment and valorization, biogas technology can cause considerable emissions of greenhouse gases (GHGs), notably methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) in the wastewater treatment process and during the biogas production and use (Chaouali et al., 2021; Hijazi et al., 2016; Naja et al., 2011; Poeschl et al., 2012). For example, emissions from anaerobic digestion of solid wastes in Tunisia represented 5% of the total raw emissions in 2000, of which emissions from wastewater treatment represented 17.2% ("Inventaire des gaz a effet de serre en tunisie pour l'annee 2000", 2000). Also, according to a study by the German Agency for International Cooperation (GIZ) focusing on emissions from wastewater treatment in 2014, those were estimated to reach 741 kt CO_{2eq} in 2020 and 815 ktCO_{2eq} in 2030 ("Convention cadre des nations unies sur les changements climatiques premier rapport biennal de la tunisie", 2014). Accordingly, the emissions from treatment and valorization should be quantified and controlled to reduce the impact of such a technology on the environment. Several papers have previously focused on this problem for different case studies, mainly in high-income countries with long experience using biogas for electricity (Chaouali et al., 2021). For example, Blanco et al. (2016), Tauber et al. (2019), and Szabo et al. (2014) quantified emissions from WWTPs in Spain, Austria, and Hungary (Blanco et al., 2016; Szabó et al., 2014; Tauber et al., 2019). However, few estimated emissions from biogas use in upper-middle-income countries, and none were found in lower-middle-income countries (Chaouali et al., 2021). For instance, the quantification of emissions from WWTPs in Colombia was done by Meneses-Jacome et al. (2015) and in Mexico by Paredes et al. (2019) (Meneses-Jácome et al., 2015; Paredes et al., 2019). As far as the authors of this study have appraised, in the case of Tunisia, single research by Adouani et al. (2015) investigated the impact of the temperature on N_2O and nitric oxide (NO) emissions in a wastewater treatment plant that does not have a biogas production unit in Tunisia; however, it did not consider the emissions of CH_4 and CO_2 (Adouani et al., 2015).

Therefore, this study aims to predict the potential GHGs emissions (CH_4, CO_2, and N_2O) from WWTPs in Tunisia if biogas units are installed to clarify the country's future emissions scenario. A reference WWTP plant was selected as the case study - Gafsa WWTP and a combination of different emission estimation methods will be employed for each wastewater treatment and valorization process occurring in the plant. The goal is to provide a comprehensive evaluation that can stimulate practitioners to limit potential emissions and insights for future sustainable water reuse and electricity generation.

The second chapter describes the selected case study. Following the third chapter focuses on the explanation of the emission estimation methods. The fourth chapter states the results and respective discussions. Finally, the last chapter concludes with the implications and a summary of the main findings.

2. The Gafsa Wastewater Treatment Plant

Biogas production is not a widespread technology in Tunisia and is just starting in some industries such as WWTPs (El Houda et al., 2020). The three existing digesters in 3 different WWTPs are no longer working ("Etude sur le développement de la méthanisation industrielle", 2010).

However, in 2018, an existing WWTP located in the Gafsa region in southwest Tunisia was renovated, and anaerobic digestion and cogeneration plants were installed (Figure 1).

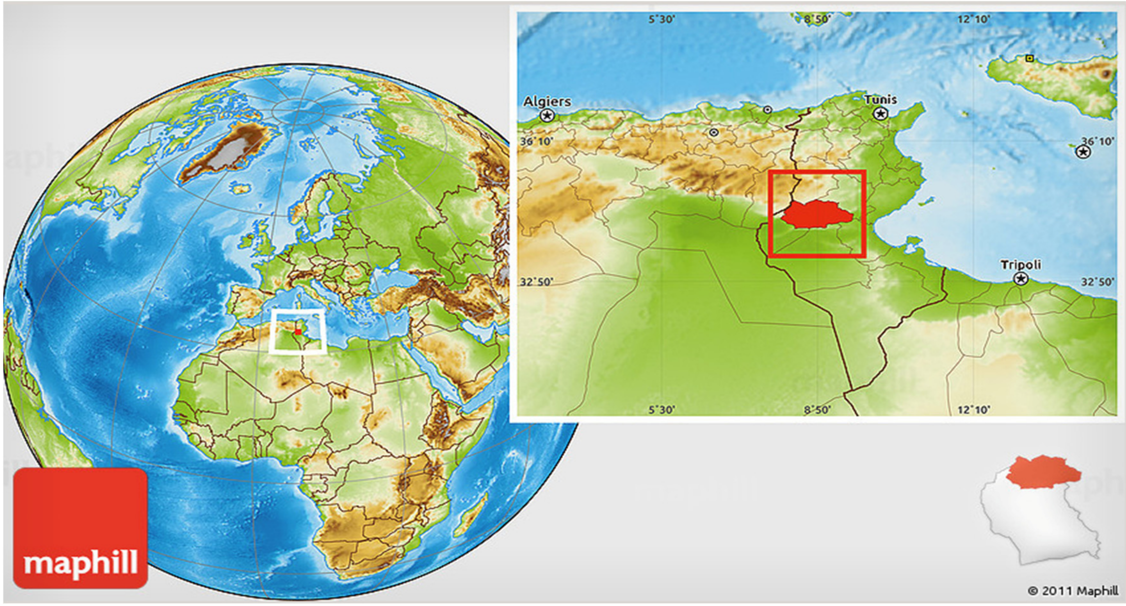

Figure 1. Location of Tunisia and Gafsa (in red) (Maphill, n.d.)

The rehabilitation works done in this WWTP aimed to expand the capacity of treatment, valorize the extracted sludge in energy production, and improve the environmental status and quality of the treated wastewater for reuse in the agricultural areas, specifically for the Aqeela area of Gafsa and industrial units around the plant, for example, the chemical group industry of the region (Figure 2). Therefore, this study will focus on the Gafsa WWTP for emissions estimation as a reference facility for the whole country.

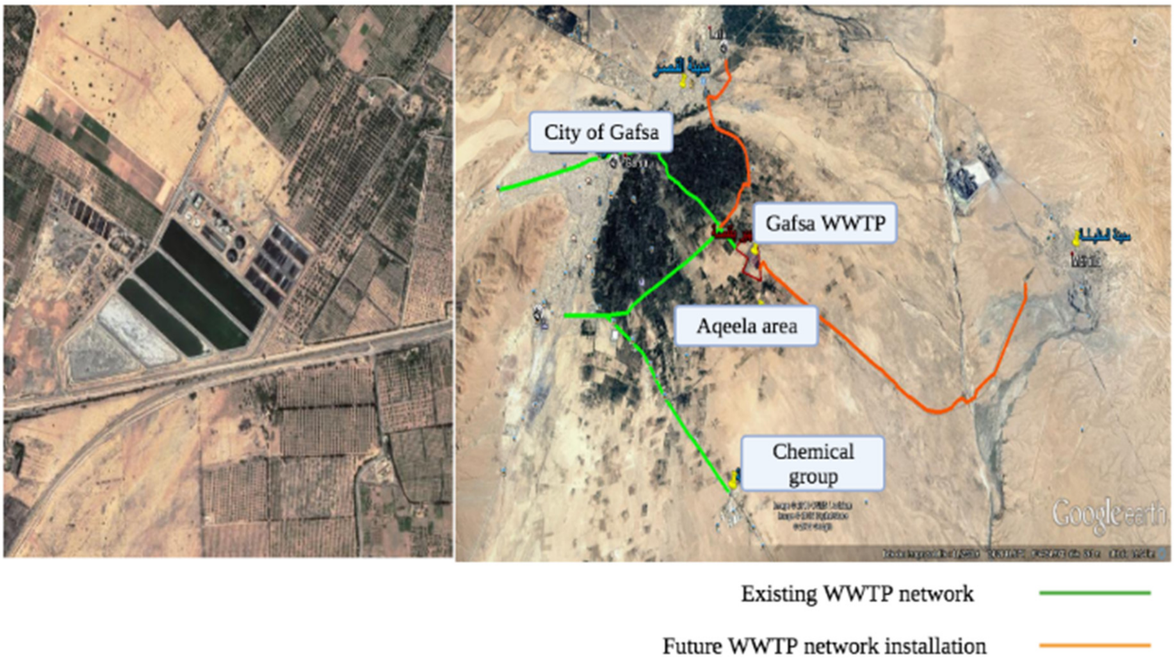

Figure 2. Location of Gafsa WWTP and its connected areas ("Work progress of the project of refining and expanding the wastewater treatment plant of gafsa", 2016)

After the rehabilitation works, the treatment plant's capacity became 14 000 m^3/day serving 184 000 inhabitants, and the average daily flow of wastewater is 13 928 m^3. The biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) fluxes are 9091 kg/day and 8278 kg/day. The plant is equipped with two anaerobic digesters and two cogeneration engines. The volume of each digester is 2746 $m^{3,}$ and the expected production of biogas per day is about 3350 m^3, which leads to an expected hourly CH_4 production of about 250 Nm^3. The electrical power produced by each cogenerator is 330 kWe, and the thermal power is 424 kWth. For this purpose, two cogenerators with hourly consumption, each 110 Nm^3/h, were installed.

The wastewater treatment process at Gafsa starts with a screening for the big rough wastes. Then, the primary treatment where the scum and fats of the waste float on top of the open settling tank and the other sludge and heavy substances settle to the bottom. The next step is the activated sludge process (also called biological treatment) with microorganisms to degrade the dissolved pollutants. Another settling step is an open tank to remove the rest of the solid matter in the water before it is discharged into sewers. Next, the sludge from all the wastewater treatment stages is collected and treated in a gravity thickener to remove the excess water. Then, the thickened sludge is sent to the biodigester, where the anaerobic digestion and the biogas are produced. Biogas is then treated in the upgrading plant to separate biomethane from other impurities that may damage the cogeneration plant, the last step. And finally, a unit for sludge dewatering after anaerobic digestion for its later use as agricultural fertilizer. Figure S1 in supplementary material presents a schematic overview of the process at Gafsa WWTP, from wastewater treatment to biogas production.

3. Methodology

In a previous study by the authors, a systematic review was conducted, and several methods for emissions estimation were identified (Chaouali et al., 2021). Based on that, three previous studies that used estimation methods specific to each process were selected as the basis for this study (Bani Shahabadi et al., 2010; Doorn et al., 2019; Robescu & Presură, 2017). Those studies offered a comprehensive and direct explanation of the estimation methods used for each of the processes covered in this research. In addition, these studies were based on various thorough methods from the literature, considering that each process has different specificities and causes of emissions, and only one methodological approach cannot be applied to all the cases. Both Shahabadi et al. (2010) and Robescu et al. (2017) referred to the study of Cakir and Stenstrom (2005) and Metcalf and Eddy (2003) for the estimation of emissions from the aerobic and anaerobic processes because of the detailed mass balances and internal reactions description not dedicated to specific case studies, which makes these equations applicable to any other study (Bani Shahabadi et al., 2010; Cakir & Stenstrom, 2005; Robescu & Presură, 2017; "Wastewater engineering treatment and reuse", 2003).

Regarding the emission sources considered in the emissions counting, the selection was based on the mode of operation of the plant and the data availability.

It was assumed that the plant operates 365 days every year for the annual emissions calculation. Only emissions from external electricity consumption (CO_2) were counted for the off-site or indirect emissions since data about chemicals use and transportation are unavailable. For on-site or direct emissions, emissions from the activated sludge process were estimated for the wastewater treatment process since, in this step, the wastewater still contains an essential quantity of organic matter, and chemical degradation is taking place aerobically. The other sources of emissions are the anaerobic digester and cogeneration engine (Bani Shahabadi et al., 2010; Robescu & Presură, 2017).

Finally, the N_2O emissions were calculated using the Intergovernmental Panel on Climate Change (IPCC) guidelines (Doorn et al., 2019).

The estimation results for Gafsa WWTP were then extrapolated to the national level by calculating the population equivalent emissions and multiplying it by the number of people connected to the wastewater treatment network. Gafsa WWTP's data for 2021 has been provided by Gafsa WWTP and were used for the estimation ("STEP Gafsa 2021", 2022). Most recent found data have been used, and estimations were made for the year 2021.

Table 1 present the input data and respective sources, and the last step of estimation calculation is shown in this paper. The complete calculation steps and procedures can be found in the Supplementary Material.

3.1 Emissions from Electricity Consumption

A WWTP needs electricity to operate, for instance, for the building lighting, for specific processes such as settling tanks, activated sludge tanks, and others. Some of these processes are very energy-intensive, suggesting that such a kind of emissions should be considered in the plant's total emissions (Bodík & Kubaská, 2013).

Emissions from electricity consumption are generally calculated by multiplying the quantity of electricity consumed by the adequate emission factor (Kopsakangas-Savolainen et al., 2017; Robescu & Presură, 2017). The CO_2 off-site emissions from electricity were calculated as follows:

$$CO_{2elect} = C_{elect} \times EF_{elect} \tag{1}$$

Where:

CO_{2elect}: Emissions from annual electricity consumption (kg CO_{2eq}/year); C_{elect}: the quantity of electricity consumed by the WWTP in the year (MWh/year); EF_{elect}: the annual average of CO_{2eq} emission factor for the electricity in the year (gCO_{2eq}/kWh).

3.2 Emissions from Activated Sludge

The activated sludge process is the most energy-intensive and associated with actual emissions in the wastewater line (Leu et al., n.d.). However, these emissions are mainly CO_2 emissions, and there are negligible or non-CH_4 emissions from this process (Robescu & Presură, 2017).

The activated sludge process is qualified as an aerobic process. Thus, the amount of oxygen needed for the decomposition of organic matter characterizes the efficiency of this treatment. On the other hand, the BOD content reflects the intensity of the potential emissions. The total emissions from the activated sludge process were calculated as follows (Robescu & Presură, 2017):

$$CO_{2as} = Y \times O_{as} \tag{2}$$

Where:

CO_{2as}: total GHG emissions kg for activated sludge process, (CO_{2eq}/day); Y: production factor of CO_2 in the aerobic process with activated sludge, (kg CO_2/kg BOD_5); O_{as}: the amount of oxygen (O_2) needed for the process with activated sludge, [kg O_2/day]. In this research, it was considered that 1 kg of BOD requires 0.55 kg of O_2 in the activated sludge process (Environmental Dynamics International, n.d.).

3.3 Emissions from the Anaerobic Digester

According to Shahabadi et al. (2010), two types of emissions can occur in the anaerobic digester: CH_4 and CO_2 (Bani Shahabadi et al., 2010). The causes of emissions in the anaerobic digester are the decomposition of organic matter into gaseous CH_4 and CO_2 and dissolved CH_4 in the effluent. The CH_4 emissions were calculated as follows:

$$CH_{4ad} = CH_{4BOD} + \left(0.35 \times CH_{4deg}\right) \tag{3}$$

Where:

CH_{4ad}: mass of CH_4 production in the anaerobic digester (kg CH_4/day); CH_{4BOD}: mass of CH_4 production because of BOD utilization (kg CH_4/day); CH_{4deg}: the amount of biomass decayed indigenously inside the reactor (kg VSS/day).

The CO_2 emissions were calculated as follows:

$$CO_{2ad} = (0.27 \times r_{BOD}) + \left(0.58 \times CH_{4deg}\right) \tag{4}$$

Where:

CO_{2ad}: mass of CO_2 production in the reactor (kg CO_2/day); r_{BOD}: total BOD needs in the anaerobic reactor (kg BOD/day).

3.4 Emissions from Cogeneration

The emissions in the cogeneration plant occur because of the combustion of upgraded biogas in the engine and were calculated as follows (Bani Shahabadi et al., 2010):

$$CO_{2comb} = \left(2.75 \times CH_{4prod}\right) \tag{5}$$

Where:

CO_{2comb}: mass of CO_2 production by CH_4 combustion (kg CO_2/day); CH_{4prod}: mass of CH_4 production (kg CH_4/day).

3.5 Nitrous Oxide Emissions

Wastewater and wastewater-related activities are the fifth major contributor to worldwide N_2O emissions ("United nations framework convention on climate change", 1992). Therefore, estimating N_2O emissions is often an essential part of any research about wastewater treatment and biogas where nitrification and denitrification processes usually occur, with several papers fully dedicated to this topic (Daelman et al., 2013; Do Amaral et al., 2018; Mikosz, 2016; Ramírez-Melgarejo et al., 2020; Wang et al., 2014). However, no field measurement or specific method can be used in this research because of a lack of data. Therefore, N_2O emissions were calculated using the IPCC method for domestic wastewater (Doorn et al., 2019):

$$N_2O_{plant} = (U \times T \times EF) \times TN \times (44/28) \tag{6}$$

Where:

N_2O_{Plant} = N_2O emissions from domestic wastewater treatment plants in inventory year, kg N_2O/yr; TN = total nitrogen in domestic wastewater in inventory year, kg N/yr; U = fraction of population in income group in inventory year; T = degree of utilization of treatment; EF = emission factor for treatment, kg N_2O-N/kg N. The emission factors in this section are given by IPCC guidelines for Tier 1. In addition, the annual per capita protein supply in Tunisia was used to estimate total nitrogen in wastewater ("*Per Capita Protein Supply*,"n.d.).

3.6 Estimation of Emissions on a National Scale

The emissions from each source are calculated and then multiplied by the corresponding global warming potential (GWP) over 100 years provided by IPCC guidelines (GWP_{CH4} = 25 and GWP_{N2O} = 298) to obtain the number of emissions in CO_2 equivalent (CO_{2eq}) (Doorn et al., 2019).

In Tunisia, the WWTP of Gafsa is currently the only one producing biogas. As mentioned previously, the governmental plan includes the installation of anaerobic digesters and cogeneration units in all WWTPs nationwide. Although there is still a debate about generalization from case studies to national or global scale, many scientists defend extrapolation from case studies and consider it a means for statistical inference in the case of unavailability of specific data for wider groups than those of the study area (Polit & Beck, 2010). Also, global generalization may be subject to high uncertainty, and the method of extrapolation can never be fully justified, but in the case of quantitative research, using a case study for national generalization may be justified by the fact that specific indicators may not vary too much for the same country especially if the area is small (Wikfeldt, 1993). Therefore, in this research, the estimation of emissions from all the WWTPs in Tunisia was calculated based on the data of Gafsa WWTP. Following a statistical generalization approach, the population equivalent (PE) emissions from each process considered are estimated and then multiplied by the population connected to the wastewater treatment network at the national scale, which is 6.470 million inhabitants in 2018 (Khrouf, 2020). Currently, the WWTP of Gafsa serves 184 000 inhabitants.

$$Emissions_{country} = (Emissions_{GafsaWWTP} \div 184000) \times 6470000 \tag{7}$$

Table 1. Input data sources and values

Process	Variable	Value	Source/Reference
Electricity consumption	C_{elect} (KWh/year)	1 924 286	(STEP Gafsa 2021, 2022)
	EF_{elect} (gCO_{2eq}/kWh)	0.57	(Takahashi Kentaro, 2021)
Activated sludge	Y (kg CO_2/kg BOD_5)	1.375	(Robescu & Presură, 2017)
	O_{as} (kg O_2/day)	5000	(Environmental Dynamics International, n.d.)
Anaerobic digestion	CH_{4BOD} (kg CH_4/day)	814.77	(Bani Shahabadi et al., 2010)
	CH_{4deg} (kg VSS/day)	259.65	(STEP Gafsa 2021, 2022)
	r_{BOD} (kg BOD/day)	5857.70	(STEP Gafsa 2021, 2022)
Cogeneration	CH_{4prod} (kg CH_4/day)	905.65	(Bani Shahabadi et al., 2010)
Nitrous oxide emissions	annual per capita protein supply	36.13	(Per Capita Protein Supply, n.d.)
	T	0.34	(Doorn et al., 2019)
	EF (kg N_2O-N/kg N)	0.016	(Doorn et al., 2019)
	U	0.34	(Doorn et al., 2019)

3.7 Sensitivity Analysis

Studies that estimate emissions, especially emissions predictions, are prone to the risk of high variations and uncertainty ranges due to non-exact projected scenarios (Pianosi et al., 2016). Conducting a sensitivity analysis, in this context, is necessary when the estimation of emissions uncertainties is not feasible in order to be aware of the possible deviations in the model based on the study's assumptions (Lumbreras et al., 2015). Sensitivity analysis allows predicting the output depending on the input data variation (Hamby, 1994; Pianosi et al., 2016). In general, for a mathematical model in the following form:

$$Y \ = Z(X) \tag{8}$$

sensitivity analysis is calculated as follows (Saltelli, n.d.):

$$Si \ = \ \frac{\partial Z(X)}{\partial Xi} \tag{9}$$

In this research, the sensitivity analysis focused on the processes with the highest emissions: CH_4 emissions from anaerobic digestion and CO_2 emissions from activated sludge. The calculation was done by varying the input parameters of these two processes by ±10% with a 1% variation step. The studied input parameters were: production factor of CO_2 in the aerobic process with activated sludge (Y), amount of oxygen needed for the process with activated sludge (Oas), influent wastewater flow rate (Qi), BOD concentration in the influent (Si), BOD concentration in the effluent (S) and biomass production because of BOD utilization (Px). The effect of these parameters on the emissions was then plotted.

4. Results and Discussion

4.1 GHG Emissions from Wastewater Treatment and Biogas Production in Tunisia

The formulas presented previously were applied to the case study of Gafsa WWTP and used to estimate the countrywide emissions. The results of the estimation of emissions from the different processes and total emissions are shown in Table 2. The annual total emissions of Gafsa WWTP were 14.65 kt $CO_{2eq,}$ and the country's emissions were 515.25 kt CO_{2eq}.

In 2000, the emissions from domestic wastewater treatment in Tunisia were 130.62 kt CO_{2eq} representing 10.1% of the total emissions from the waste sector, which suggests that emissions from wastewater treatment are continuously increasing even with the introduction of biogas and cogeneration technologies to reduce the WWTP carbon footprint (Gustavsson & Tumlin, 2013).

Table 2. Emissions quantities from different processes of case study and country

Process & emission type	Emissions of Gafsa WWTP (kt CO_{2eq})	Emissions from all WWTPs in Tunisia (kt CO_{2eq})
Off-site electricity (CO_2)	1.10	38.57
Activated sludge (CO_2)	2.51	88.24
Anaerobic digestion (CH_4)	8.26	290.59
Anaerobic digestion (CO_2)	0.63	22.23
Cogeneration (CO_2)	0.91	31.96
Nitrous oxide emissions (N_2O)	1.24	43.65
Total emissions	14.65	515.25

The increase in emissions is also explained by the rise of the number of WWTPS in the country, which evolved from 60 in 2000 to 123 in 2020, and the number of connected people to the wastewater treatment network ("Official website of ONAS", 2022). The high emissions also reflect the flaws in the current waste management strategies leading to significant unsolicited emissions. In Tunisia, the National Sanitation Office (ONAS) and the National Waste Management Agency (ANGed) are the institutions appointed by the ministry of environment and responsible for wastewater and waste management. In their integrated and sustainable wastewater and waste management strategy report, they state that many problems are contributing to the failure of these strategies essentially: lack of consultation, cooperation, and communication between the various stakeholders to implement projects of energy production from waste and wastewater smoothly; rapid evolution of waste and wastewater quantities in a way that exceeds the capacities of treatment plants; absence of a preventive approach in the treatment of waste and wastewater; inadequate environmental awareness and education activities and programs about the importance of control and management of all types of wastes; slow development of management systems for some waste streams; weak participation of the private sector in the production of electricity from wastes which increases the burden of investment costs on the government; limited financial resources to cover waste and wastewater management costs ("Gestion intégrée et durable des déchets", 2006).

The CH_4 emissions from anaerobic digestion were 290.59 kt CO_{2eq} and had the highest share of the total emissions (56%), while CO_2 emissions from anaerobic digestion were only 22.23 kt CO_{2eq} (4%). During anaerobic digestion, biomass is decomposed into biogas, and since CH_4 is the main component of biogas, the emissions from this process are essentially CH_4 emissions. Also, the impact of CH_4 on the environment is more substantial than CO_2, and consequently, it has a higher global warming potential (GWP_{CH4} = 25 and GWP_{CO2} = 1), so the quantity of CH_4 in CO_{2eq} is more important from the same process. According to Tauber et al. (2019), CH_4 emissions are caused by digester leakages, gas bubbles, dissolved CH_4, and residual gas potential in the sludge retained in the reactor (Tauber et al., 2019). Cakir and Stenstrom (2009) state that the mass of dissolved CH_4 in the effluent during anaerobic digestion can be as high as the recovered CH_4 (Cakir & Stenstrom, 2005).

Additionally, Lobato et al. (2012) found that dissolved CH_4 can reach up to 18% of the produced CH_4 and 10% of the gas potential in the sludge retained in the digester (Lobato et al., 2012). Another research expresses the previous sources of CH_4 emissions degraded inside the reactor (Bani Shahabadi et al., 2010). To minimize emissions from anaerobic digestion, checking and maintenance of the digester for leakages should be done regularly (Hijazi et al., 2016).

The country's emissions from electricity consumption were 38.57 kt CO_{2eq} which were the fourth-highest emissions (8%). The electricity consumption of Gafsa WWTP was 1.10 kt CO_{2eq}; however, it can be higher in other larger WWTPs that have more complicated energy-consuming processes. Nevertheless, electricity consumption is generally one of the primary emissions sources in the wastewater field (Blanco et al., 2016; Maktabifard et al., 2019). In Tunisia, all the electricity from renewable energies is injected into the national electricity grid, and therefore all the electricity consumption of the WWTP should be taken from the grid (BELET CESSAC). Therefore, even if the WWTP produces electricity from biogas, it does not cover the plant's need but rather inject it back into the grid, and the WWTP benefits from cheaper electricity bills. According to Hijazi et al. (2010), minimizing the parasitic electricity consumption is the solution to reduce electricity consumption as well as the use of the output electricity from cogeneration which can be applied to Tunisia if the regulation changes in the future and the plant become able to use the produced electricity from cogeneration for its use (Hijazi et al., 2016).

Emissions from cogeneration were 31.96 kt CO_{2eq} representing 6% of the total emissions. These emissions correspond to the exhaust gas of the complete and/or incomplete combustion of biogas in the cogeneration engines. Those can be avoided by using the carbon capture technique, and CO_2 can then be used to synthesize gas production (Rafiee et al., 2021). Cogeneration engines with higher capacity can also have less carbon footprint than the small ones (Budzianowski & Postawa, 2017). Therefore, by enhancing the thermal and electrical efficiency of cogeneration engines, emissions to the air can be reduced (Hijazi et al., 2016; Rafiee et al., 2021).

CO_2 emissions from the activated sludge process were 88.24 kt CO_{2eq} and were the second-highest source of emissions (17%). In this step, the air blowing during the dissolution of organic matter in the aerated tank is responsible for these emissions (Kyung et al., 2015). In Tunisia, activated sludge is the most used process for secondary wastewater treatment besides settling tanks (De L' & Abroug, 2014). That suggests that adequate measures need to be taken to limit its emissions. Yapıcıoğlu (2020) proposes the change of operational conditions like the reduction of hydraulic retention time and solid retention time as a measure to reduce emissions from activated sludge (Chen et al., 2016; Yapıcıoğlu, 2021). In this research, only CO_2 emissions from activated sludge have been calculated; however, other studies suggested that there are also other emissions such as nitrous oxide, hydrogen sulfide, and methyl mercaptan, but there is no applicable estimation method for this research (Cui et al., 2022; Joon Ho Ahn, Sungpyo Kim, Hongkeun Park, Brian Rahm , Krishna Pagilla, 2010).

Following the consideration that emissions other than CO_2 should be accounted for, the general N_2O emissions were calculated according to IPCC guidelines, resulting in 43.65 kt CO_{2eq} (9%), making it the third-highest source of emissions (Doorn et al., 2019). Those emissions can occur because nitrification and denitrification occur in different processes in the plant, such as the activated sludge process (Rodriguez-Caballero et al., 2015). Furthermore, according to a study by Daelman et al. (2013), N_2O emissions increase in winter because the decrease in the temperature leads to longer sludge retention time which results in a lower nitrification rate (Daelman et al., 2013; Wang et al., 2014). However, this estimation does not cover the emissions of effluent discharged into the environment, which is also an important source of emissions mainly because such practice is frequently used in Tunisia (*Etude D'impact Environnemental Et Social Du Projet D'exécution Du Système D'évacuation Des Eaux Épurées De La Station D'épuration Choutrana Vers La Mer (Tronçon N1)*, 2019). According to Shichang et al.

(2015), the insufficient dioxygen supply leads to incomplete nitrification and denitrification processes, leading to higher N_2O emissions. Therefore, controlling dissolved oxygen at adequate levels during activated sludge results in less N_2O emissions (Sun et al., 2015).

The total share of CO_2 emissions from wastewater treatment and biogas production nationwide amounted to 181.00 kt CO_{2eq}. Moreover, the total contribution from CH_4 and N_2O emissions were 290.59 kt CO_{2eq} and 43.65 kt CO_{2eq}. The emissions due to biomass-to-energy from crops, farms manure, and wood combustion reported in Tunisia's 2000 GHG national report using the IPCC 2006 guidelines were 3543 kt CO_{2eq} ("Inventaire des gaz a effet de serre en tunisie pour l'annee 2000", 2000). This quantity of emissions is considerably high, and it does not even involve emissions from biomass-to-energy from wastewater treatment, as well as there is no mention of CH_4 and N_2O emissions. Thus, showing the limitation of the national inventories in covering all types of emissions, even though those have a potentially high impact on the country's total emissions. Usually, these kinds of national inventories focus more on energy, transportation, and manufacturing emissions because these sectors have a higher impact on the environment. However, accumulation from other sectors, such as wastewater treatment, can also affect the total counting of emissions. Furthermore, this research has shown that, even without considering the CH_4 emissions, emissions from wastewater treatment are already high for some processes such as activated sludge, electricity consumption, and nitrous oxides emissions. Though, since many factors contribute to that, a country like Tunisia needs to enhance, at the same time, the treatment of water and energy production to overcome its lack of both electricity and water resources, which explains the necessity of knowing and calculating any emissions that can be caused by biogas use.

4.2 Sensitivity Analysis

Sensitivity analysis of CO_2 emissions from activated sludge and CH_4 emissions from anaerobic digestion has been studied to understand the influence of each activity data and/or operational condition on the variation of emissions. Emissions from the activated sludge process vary similarly to the variation of Y and O_{as} (Figures 6a and b). They can reach a minimum of 79.41 ktCO_2eq/year and a maximum of 97.06 ktCO_2eq/year. As for calculations, the variation of the production factor of CO_2 in the aerobic tank is a determinant of the accuracy of the emissions. Also, regarding the operational condition of the plant, the increase in the intensity of oxygen in the biological process leads to an increase in the emissions and vice versa.

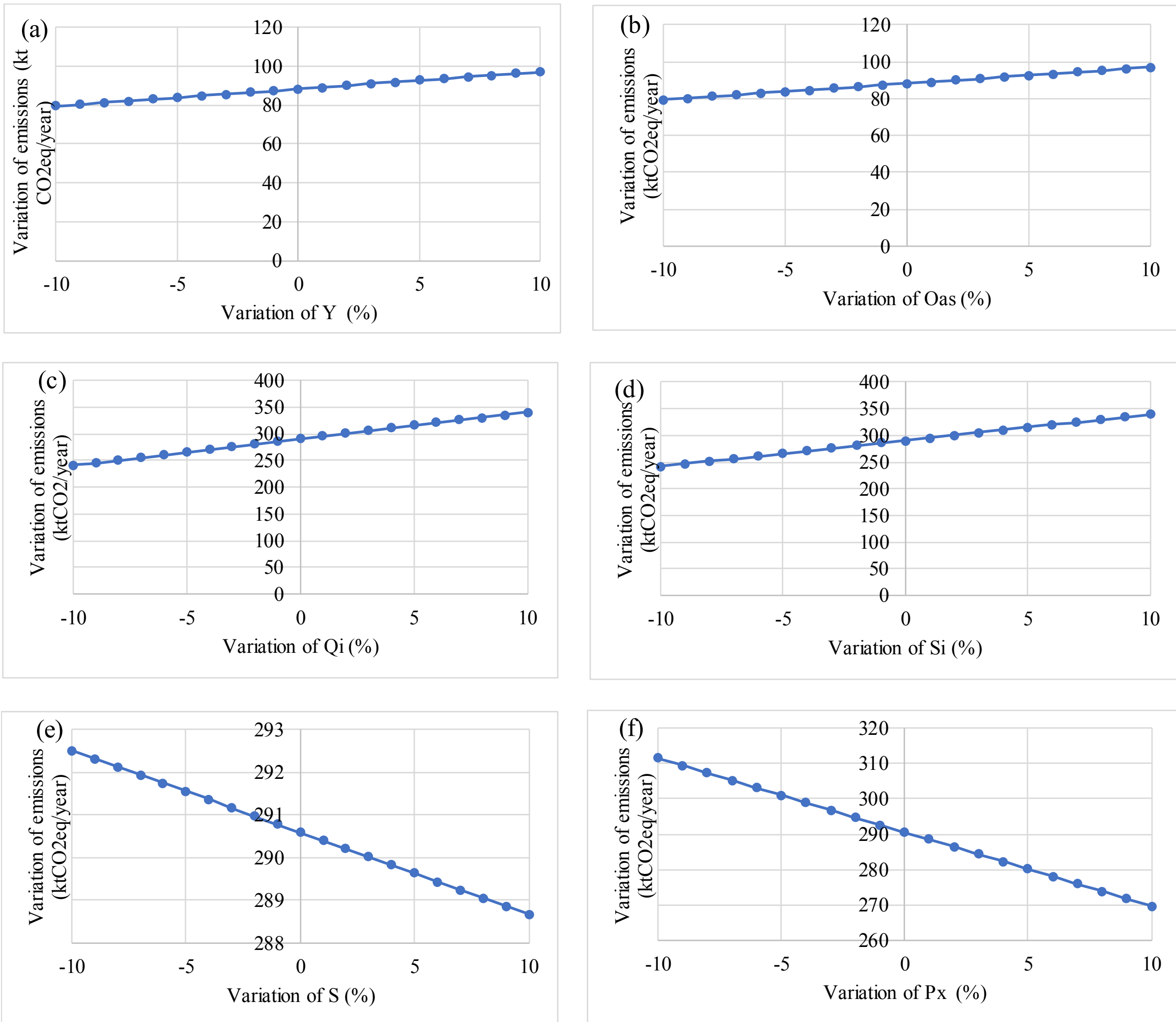

Figure 3. Variation of emissions with input parameters

CH_4 emissions from anaerobic digestion increase with the increase of Qi and Si (Figures 6c and d) and decrease with S and Px (Figures 6e and f). These emissions can be diminished to 240.69 ktCO$_2$eq/year and go up to 340.49 ktCO$_2$eq/year. The influent wastewater flow rate increase has the highest effect on the increasing emissions. The increase in biomass production because of BOD utilization contributes the most to reducing emissions. Consequently, applying different operational options in the WWTP to control these key emissions factors may be the solution to manage the plant's total emissions. Additionally, updating emission factors or calculating specific ones for the plant can also reflect more reliable results in the emissions estimation.

5. Conclusion

This research showcases a pilot study to predict GHG emissions from WWTPs if biogas production and cogeneration are installed. Biogas is a promising technology for Tunisia and is at the same time a solution for wastewater treatment and management, water stress, and electricity needs. Treated wastewater can be used for agriculture, collected sludge can undergo anaerobic digestion, and the biogas produced can be used in cogeneration engines. However, the emissions from the wastewater treatment sector with biogas production were relatively high (515.25 kt CO_{2eq}).

In total, CH_4 emissions were the highest type of emissions, followed by CO_2, and the minor emissions were nitrous oxides. CH_4 emissions from anaerobic digestion were the most important source of emissions (290.59 kt CO_{2eq}), followed by CO_2 emissions from the activated sludge process (88.24 kt CO_{2eq}), N_2O emissions (43.65 kt CO_{2eq}), electricity consumption (38.57 kt CO_{2eq}), cogeneration (31.96 kt CO_{2eq}) and finally, CO_2 from anaerobic digestion (22.23 kt CO_{2eq}). The governmental institution's existing reports of emissions inventories did not cover all types of emissions from wastewater treatment. Consequently, this research is essential to understand the potential emissions profile when biogas is installed and the good practice to limit them. This kind of research can also help increase the social acceptance of biogas by providing information on potential emissions and encouraging investors and private parties to participate with governmental institutions by pointing out the emission issues related to biogas production.

Nevertheless, the lack of specific data made this study limited to emissions estimation from only specific processes in the plant (activated sludge process, anaerobic digestion, cogeneration). In addition, the extrapolation of the emissions on a national level was only based on the 2018 number of populations connected to the wastewater treatment network (6.470 million people). Therefore, future studies could estimate emissions from other processes like secondary treatment tanks and biogas upgrading and should be based on the most recent number of connected people to the wastewater treatment network. Moreover, this estimation of the future emissions from wastewater treatment and biogas production in Tunisia has been done following theoretical methods. Direct emissions measurement on-site would provide more reliable results and allow for relevant comparisons of the predicted emissions.

The findings of this study can be used to evaluate the impact of emissions on the environment and human health through applying a life cycle approach and the conversion of relevant health indicators.

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