Doctoral Dissertation

Management of Greenhouse Gas Emissions of Biogas from Wastewater Treatment in Tunisia Based on Life Cycle Thinking

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Abstract

In order to meet national goals and international standards to reduce greenhouse gas emissions and limit climate change effects, all the countries are required to revise their activity sectors and identify emissions hotspots and control them. Some regions are more threatened by climate change impacts than others, notably the Middle East and North Africa (MENA) region. In the same context, Tunisia is one of the countries of MENA region aiming at reducing the environmental impacts from wastewater treatment sector and increasing the share of biogas production by 2030. Despite the high connection rate to wastewater treatment network in Tunisia, it is still facing many struggles to advance. For instance, emissions from both wastewater treatment and biogas should constantly checked and managed. Therefore, this thesis studied thoroughly the present situation of biogas sustainability from an environmental point of view in Tunisia since the biogas technology is still not well spread and assessed even though it represents a potential solution for waste management.

In the second chapter, a systematic review exploring past research about emissions from biogas especially in wastewater treatment plants was conducted. Several screening phases and criteria allowed to select most relevant papers in this topic. The most highlighted findings stated that the primary sources of emissions were aerobic treatments of wastewater and anaerobic digester leakages. The most used methods to estimate emissions varied from theoretical methods like international guidelines or other mathematical models to on-site measurements using specific tools. The most affected impacts reported from biogas were on human health, global warming, and climate change. This topic highlighted that while some countries developed advanced technologies for biogas production and advanced assessment tools, others are still with little to no experience in this field.

In the third chapter, the case study Tunisia was presented through its waste and wastewater management situation and objectives. This chapter explained the contradiction between achievements of Tunisia in the wastewater treatment field when it started and the issues hindering its present and future progress.

In the fourth chapter, possible greenhouse gas emissions in the case of installation of installation of biogas plants all over the country were predicted. The estimation was based on IPCC guidelines mainly in one case and a second case included selected adequate estimation equations from the literature besides IPCC and also by collecting specific plant data from Gafsa wastewater treatment plant, the representative plant in this research. This prediction revealed that emissions can reach up 126.59 kt CO_{2eq} and their main hotspots are nitrous oxide emissions from wastewater treatment by activated sludge, electricity consumption and cogeneration. However, the use of electricity produced by cogeneration to cover the plant’s needs reduced emissions from fossil electricity consumption. Best practice from other countries experiences can be applied to limit emissions in a wastewater treatment

plant. This research helped essentially to clarify the emissions profile when biogas is installed for future improvement suggestions.

In the fifth chapter, a life cycle assessment of the current wastewater treatment scenario before biogas implementation was carried to understand the environmental impact of wastewater treatment plants in Tunisia. It revealed that wastewater treatment process and sludge landfill are causing most of the environmental burden of the wastewater treatment plant. By suggesting alternative scenarios and comparing them to the present scenario, it was proven that sludge landfill should better be replaced by sludge drying and that producing biogas reduces the total impact of the plant.

The assessment of the impact of these possible opportunities is necessary to improve the wastewater treatment sector and encourage the revision of policies regulating emissions to be better respected by improving the current wastewater treatment scenario in Tunisia by including the suggested options. By doing so, Tunisia will be the pilot in MENA region of solving the slow/stagnant development in its waste management system and accomplish beneficial actions towards the situation of the region in terms of climate change effects.

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1. Introduction

1.1. Background

The global interest in solving ecological problems is growing with the increase of environmental-threatening human activities [1], [2]. The interest in environmental issues is also necessary with the growing importance of the concept of sustainability and ways to achieve it [3], [4]. Sustainability is the balance between fulfilling men's different needs (energy and goods) from available resources without overconsuming them in a way that causes problems and resources scarcities for future generations and it includes all the different activity fields [5], [6]. Therefore, environmental issues are activities that can limit the availability of these resources and good quality conditions for future life on earth [7]. One of these growing issues is climate change and global warming [8]. Climate change causes a shift in seasons and with global warming, global temperature is progressively increasing by few degrees leading to severe environmental impacts like aridity, sea level rise and water scarcity, etc [9]. For several reasons, some regions are more threatened than others. For example, Middle East and North Africa (MENA) region is the most vulnerable to land dryness and water scarcity risk. Many circumstances contributed to this higher vulnerability than the rest of the world essentially the location of the region in the earth and the variability of temperature and seasons [10]. Additionally, MENA region largely depend on agriculture and consequently any change in climate will directly affect land quality, precipitation amounts and ecosystems and as a result crops will also be affected [11]. Also, the fast population growth and related needs compared to the available resources are another reason for the higher vulnerability to climate change effects [12].

Greenhouse gas (GHG) emissions are the primary responsible for making the climate change matter even worse [13], [14]. Carbon dioxide (CO_2), methane (CH_4), nitrous oxides (N_2O) are respectively the most frequently released GHGs in the atmosphere because of human activities [15]. GHG emissions can arise from different sectors such as transport, energy, industry, etc [16]. It has been proven that energy systems are the highest responsible for emissions [17]. Lately, research focused on generating energy from sustainable sources (solar, wind, biomass, nuclear) considering that their impact is less than the one from fossil fuels [18]. However, though these energies represent a good alternative to replace fossil fuels, research showed that environmental damage can also occur from these energies. It can be caused by the resource's extraction or disposal of used materials and their related emissions.

1.2. Wastewater and biogas as energy vectors

Biogas is one of the renewable energy sources produced from organic matter that can be found in crops, solid wastes and wastewater sludge [19]. It has been widely used to produce electricity or for cooking and heating. The degradation of organic matter results in a mix of gases essentially CH_4 then CO_2 and other trace compounds [20], [21]. The process used for this degradation is called anaerobic digestion. It takes place in a designated tank called digester in the absence of oxygen and under specific conditions like temperature, pH, etc [22], [23].

On the other hand, wastewater quantities are increasing with the increasing population all over the world and needs to be collected and managed in the least damaging ways [24]. As mentioned previously, sludge extracted from wastewater can serve for biogas production. The process happens in a wastewater treatment plant (WWTP) where the wastewater treatment takes place through different steps leading to the obtaining of a quantity of sludge rich in organic matter [25]. That sludge is further treated then transported to the anaerobic digester installed in the plant to produce biogas. Biogas can be burned in a cogeneration engine to produce electricity and heat simultaneously. By doing so, biogas can help reducing waste quantities, satisfying the plant's needs of heat and providing part of the plant's needs of electricity [26].

1.3. Problem formulation and research questions

Like any other kind of energy, emissions can result from wastewater treatment and biogas [27]. It can be caused either during the treatment and processing steps and/or from the problems that can occur to the equipment in the plant and combustion exhaust gases [28]. In order to guarantee the use of this technology in the most sustainable way, it was necessary to assess its impact on the environment. Previous research proved that considerable emissions rise from wastewater treatment and biogas [28]–[31]. Some of these emissions are inevitable and others are due to poor planning and maintenance. Consequently, the opinions regarding wastewater-based biogas sustainability are still not clear because of the possible generated emissions [32], [33]. In order to shape these opinions, previous researchers based their evaluation of wastewater-based biogas benefits and harmful effects on life cycle thinking. Life cycle thinking is a technique that allows to evaluate a product not only based on its specific production chain but to also include environmental and social impacts of its whole life cycle [34], [35]. This technique allowed scientists all over the years to look at the big picture of all the possible consequences that might happen form a certain product and to be more objective regarding decision making. Thus, wastewater treatment and biogas have essentially been evaluated based on life cycle thinking to measure their pros and cons [28], [36].

Moreover, the use and research of biogas is not equally distributed all over the world. Specifically, as previously mentioned, MENA region countries face common challenges related to waste management and wastewater treatment [37], [38]. These countries generate a quantity of sludge that has a potential for biogas production [39]. They also have growing needs in energy and need to cover it. However, the wastewater collection and treatment rate are not so high and only 43% of wastewater is collected and treated [40]. Also, the biogas production is not so spread in the region although it represents a beneficial solution for wastewater in the region [41]. Until now, the electricity production in MENA relies heavily on oil and natural gas because of their availability in the region and the emissions from energy sector reached 42% of total carbon emissions in 2011 [41]. Recently, these countries were trying to increase the share of renewable energies to the energy supply. Hydropower and wind energy have the highest contribution to electricity production from renewables and biogas is one of the least produced [42].

In the same context, Tunisia is a North African country with a relatively high public sewerage network connection rate of 86.1% in urban areas compared to surrounding countries and 99% of the collected wastewater treatment rate in 2019 [43]. However, sludge disposal in landfills and the slow introduction of electricity production from biogas in WWTPs represent some evidence indicating that the performance of WWTPs in Tunisia is still not complying with sustainability [43], [44]. The achievement regarding wastewater treatment rate contradicts the slow improvements made in the sector to manage its various impacts and the implementation of new technologies. It also does not comply with the policies related to GHG emissions mitigation and goals governing the wastewater treatment sector that first aim to limit the harm from human-generated wastes [45]. Consequently, further research about wastewater and biogas emissions management is required for the case of Tunisia to give insights of paths that can be taken to improve the sector for the country and the MENA region in general and to help reduce the impact of emissions on the environment and limit the climate change effect.

1.4. Research framework and objectives

This thesis was done in the aim of positioning Tunisia's development in the field of wastewater treatment specifically the situation of wastewater-based biogas and its related emissions based on life cycle thinking. Understanding the emissions profile and their contribution to the total country's emissions is necessary to research and decide the best strategies as well as the policies revisions that need to be done in order to achieve the sustainability goals. Figure 1 represents the framework of this study.

As a first step, it is essential to investigate the state of art about biogas related emissions and explore the latest research to know the world's situation regarding this topic. Conducting a systematic review is a way to achieve that and answer the following questions: What are the sources of emissions from wastewater-based biogas and the methods to estimate them? And what are the most highlighted impacts of these emissions?

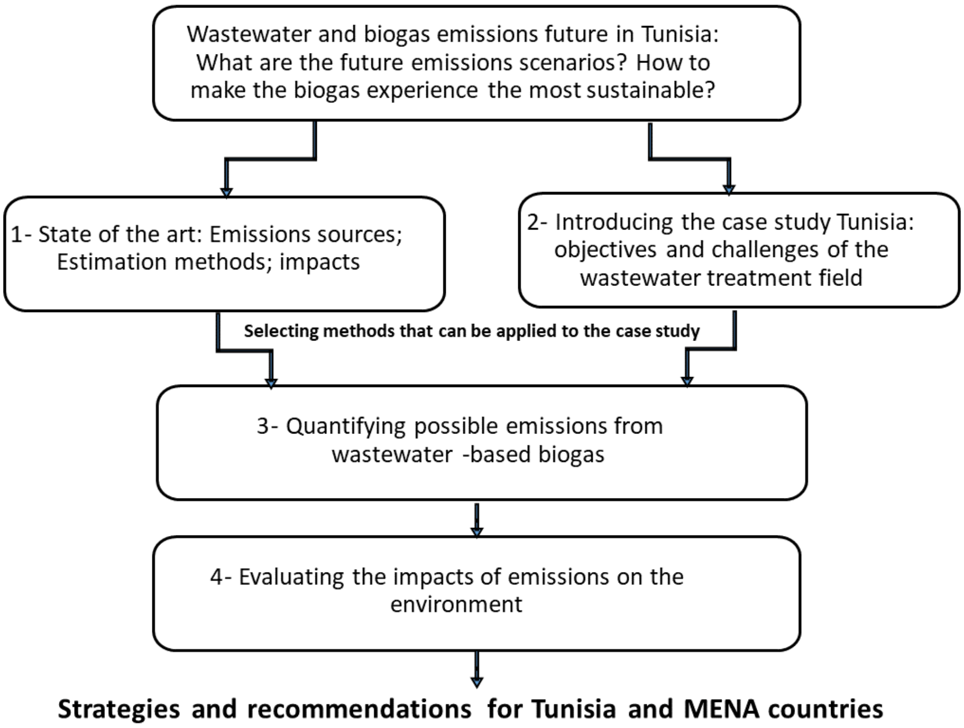

Figure 1- 1: Thesis framework

Secondly, Tunisia, the case study is presented through the situation of its waste management and wastewater treatment state to understand the challenges and objectives in this field.

After that, it is necessary to have a vision about the quantity of emissions that can arise from wastewater treatment plants if biogas is installed. This step will help to better plan the starting of biogas in terms of plant equipment maintenance requirement and best practice. Therefore, the research question is: What are the possible emissions from wastewater-based biogas in Tunisia?

Next, it is not enough to have the quantities of possible emissions generated, but it is important to understand how they damage the environment and to which extent through a life cycle assessment. This will help emphasize the necessity to take actions regarding wastewater treatment emissions and future strategies to limit the effect of their effect on climate change and global warming. This research is important not only for Tunisia, but the strategies and recommendations can also be extended to all the MENA region countries. The question answered in this part is: What is the environmental impact of wastewater treatment plants in Tunisia?

Each of these topics is explained and studied in the next chapters of the thesis.

2. Case study presentation: Tunisia

Tunisia is a country located in the north of Africa with 163,600 km^2 of area and 1,148 km of coastline. Its population reached 12.10 million in 2022. Waste management started in Tunisia since 1993. However, the field seems to not progress much compared to the available waste solutions existent nowadays [46].

2.1. Waste management in Tunisia

The daily amount of waste generated per capita is 0.60 kg in urban areas and 0.15 kg in rural areas. The quantity of municipal solid wastes generated in 2018 reached 2,686,420 Tons from which 2 million are from the 10 governorates of the Northeast and the East of Tunisia representing 75% of the total wastes. The composition of collected wastes is represented in Table 2-1.

Table 2- 1: The composition of solid waste in Tunisia

Material	Percentage
Organic matter	60 %
Plastic and paper	21 – 25 %
Recyclable matter (metals, textiles, glass) / Inert material and partially dangerous matter (medicines, batteries, aerosols)	15 – 19 %

Waste management in Tunisia is essentially governed by two texts of law, the local authorities code of 2018 and law n° 96-41 of June 10, 1996, relating to waste and control of its management and disposal.

The planning of waste management is done on three levels: national, regional and local [47]. Locally, municipalities are the primary responsible for waste removal in Tunisia. Citizens are secondary responsible for waste collection but those does not take their responsibility seriously and blame it all on municipalities. The contribution of the private sector to waste management is less than 10%.

Initially, waste is supposed to be sorted and collected in plastic bags. Those are collected by municipality employees and transported by compactor dump trucks to landfills. The creation of controlled landfills started in the end of 1990 and Borj Chakir landfill for Grand Tunis was the first to be created. Interior regions still dump their wastes in uncontrolled landfills. Additionally, while 80% of wastes in urban areas is collected, only 0 to 10% are collected in rural areas [47]. The current waste management strategy is presented in Table 2-2.

Table 2- 2: Waste management strategy in Tunisia

Strategy	Percentage
Disposal in controlled landfills	70 %
Disposal in uncontrolled landfills	21 %
composting	5 %
Recycling	4 %

2.2. Wastewater treatment in Tunisia

Wastewater treatment in Tunisia started in 1974 when the National Sanitation Office (ONAS) was established and designated as the governmental institution responsible for wastewater treatment in Tunisia [48]. Since then, ONAS has been studying domestic and industrial wastewater treatment in Tunisia and planning and executing projects in urban and rural areas. The main goal of ONAS was to provide wastewater and sanitation services to residents to guarantee good living conditions and help reduce related health problems and epidemics caused by water, soil, and air pollution from waste disposal. Added to that, with the current critical situation of water scarcity risk, it became necessary to enhance the reuse of water from wastewater treatment for agriculture, and therefore securing a good water quality is essential [49]. The connection rate to the wastewater treatment network has evolved from 20.6% in 1975 to 86.1% in 2019 and daily treated wastewater currently reached 786,000 m^3 (284 million m^3/year). By 2020, the total number of WWTPs in Tunisia reached 123. Most of the WWTPs are located in the big cities on the coastal line [48].

Overall, wastewater treatment in Tunisia uses preliminary treatment, primary treatment by sedimentation, and secondary treatment. The secondary treatment processes currently used consist of activated sludge (80%), lagoons (12%), and other processes (biological filter, filter planted with reeds, and bacterial bed) (8%). Recently, tertiary treatment by solvents was added to WWTPs located near sensitive water environments, and it is aimed to expand its use in the future [48].

The wastewater treatment sector in Tunisia faces several challenges, including the unequal distribution of WWTPs throughout the country, the improvement of the treatment process in terms of efficiency and limiting GHG emissions, and the management of the generated sludge from the wastewater treatment process [48]. Additionally, since ONAS is fully funded by the government so that it provides services adequate for the purchasing power in Tunisia, the improvement of this sector is very slow due to the limited budget [49].

In order to overcome the previously mentioned challenges, the future strategies of ONAS include installing WWTPs in small cities in the interior regions, expanding and renovating the existing WWTPs, installing the tertiary treatment of wastewater in more plants, and increasing the sludge drying rate, especially in the big WWTPs, increasing the contribution of wastewater treatment sector to the energy production by cogeneration, limiting the emissions of GHG from wastewater treatment and increasing water reuse rate [43].

By working on these issues, Tunisia can safeguard better life conditions to its citizens and achievements in its sustainable development goals (SDGs). By 2022, Tunisia marked progress for the 6th and 13th SDGs about clean water and sanitation and climate action and is moderately improving in the 7th goal, which is affordable and clean energy [50].

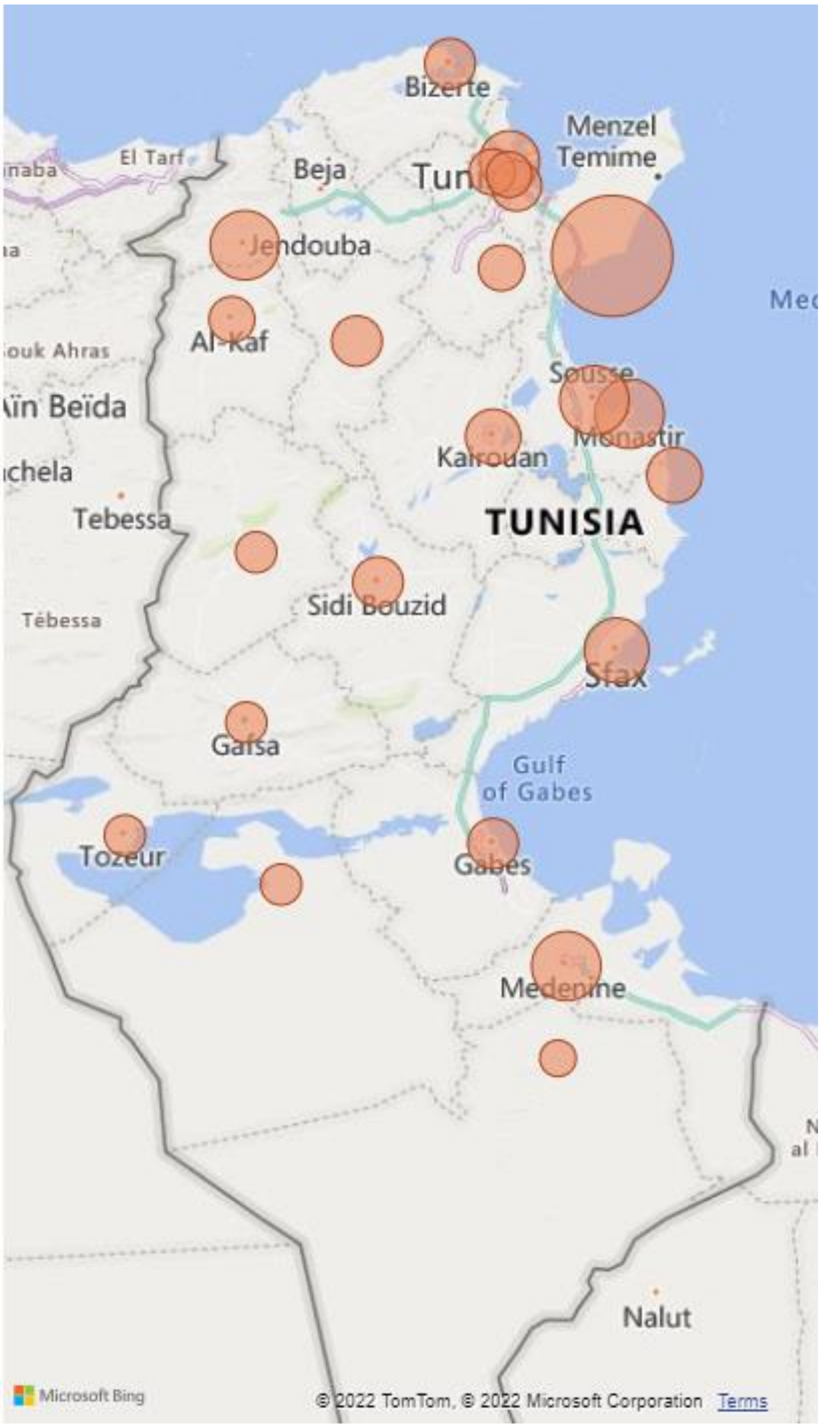

Figure 2- 1: Distribution of WWTPs in Tunisia

There are 123 WWTPs currently working in Tunisia distributed all over the 24 regions (Figure 6). However, the distribution is unequal. For example, while the region of Nabeul - located in the northeast of Tunisia and very close to the capital- has 19 WWTPs, the region of Tataouine, located in the south of Tunisia, has only one WWTP. WWTPs in Tunisia can be classified based on their treatment capacities as follows: large scale plants > 10,000 m^3/day; medium scale plants 1,000 m^3/day- 10,000 m^3/day and small-scale plants < 1,000 m^3/day. The information about the starting year, each plant's capacity, and their regional distribution are shown in Table B1 in the appendix.

2.3. Waste and wastewater policies and goals in Tunisia

The national constitution of 2014 dealt with issues related to climate, environment and natural resources management. Articles 12 and 45, respectively, emphasize "the rational exploitation of resources" and the role of the State in ensuring "the right to a healthy and balanced environment and the participation in the protection of the environment". Article 129 highlights the fact that "law projects relating to economic, social, environmental and environmental issues, as well as for development plans" must be based on the principles of respect for "sustainable development and the rights of future generations" [51].

Tunisia is one of the few developing countries to have included, from 80s, sustainable energy development in its strategy and implementation of policies and energy efficiency measures.

The laws and policies regulating waste and wastewater management in Tunisia are: National Water and Sanitation Policy, National program to fight climatic change, National Waste Management Policy: Law 1996-41 of 10/6/1996 on waste, control of its management and disposal; the Law 1975-33 of 14/05/1975 on the Organic Law of the Municipalities entrusting the collection of waste and Decree No. 726-1989 of 10 June 1989 on councils' rural people entrusting the disposal of waste in rural areas to elected councils.

3. Identification of Most Affected Impact Categories of Wastewater-based Biogas Production and Use

3.1. Introduction

Recently, the world has shifted from the exclusive use of fossil fuels to renewable energy sources [52]. The environmental impact of a technology is an essential factor in decision-making matter, especially with the incessant increase of global warming and climate change [53].

Hence, the present effort has been on reducing impact of energy production caused by traditional sources and their compensation by renewable energy sources such as biogas [54]. Biogas is produced in a system that provides suitable conditions to efficiently degrade material like crops and wastes into methane and carbon dioxide [55]. At the same time, there is an increase in the quantities of wastewater generated and untreated in the world. If wastewater is adequately treated, huge amounts of sludge produced from the process can serve for biogas production. Biogas can then be used for electricity and heat, reducing the need for fossil fuels and the overall emissions to the environment [56], [57]. Therefore, compared to other renewable energy sources, besides the benefit of electricity production, biogas has the advantage of being a solution to dispose of sludge generated from wastewater treatment that can occupy large areas and emit toxic gases if landfilled, as well as simultaneously producing thermal energy and providing organic fertilizers to boost agricultural crops [58].

Various previous research studies highlighted the importance of installing biogas production units in WWTPs and emphasized its numerous benefits, including its positive environmental impact compared to fossil fuels. Nonetheless, their focus was limited to considering the net emissions savings only [59]. At the same time, researchers also noticed that biogas production and use from wastewater can be associated with GHG emissions consisting essentially of CH_4, CO_2, N_2O and can represent a potential hazard [60]. For instance, Vasco-Correa et al. (2018) argued that in terms of emissions, while producing electricity from biogas is beneficial when it is compared to electricity coal-fired power plants, it cannot be beneficial compared to natural gas or an electricity grid system that includes other renewable energy sources [61]. This witnesses that there is a lack of agreement and there are two opinions concerning biogas sustainability: one does not acknowledge emissions from wastewater-based biogas and the other one encourages the estimation and reduction of emissions. The diversity of viewpoints described above, contributes to the slow spread of this technology worldwide [61], [62]. It also points to the critical need to clarify and update information about the biogas emission processes to allow its sustainable adoption and implementation with the least unintended negative impacts to people and the environment.

Therefore, this topic aims at answering the following research question: *what are the recent scientific research advancements concerning the emissions from production and use of biogas from wastewater?* This is done by conducting a systematic review with the following specific objectives: clarify the status of recent literature on emissions from wastewater-based biogas production and use; identify the critical sources of emissions, identify, and describe the existing emission estimation approaches, and classify and evaluate the most significant environmental impact categories.

3.2. Materials and methods

3.2.1. Systematic literature review

Systematic literature review was used to explore this topic. It is an evidence-based research methodology that allows understanding what is known and what is not known yet about a particular topic. It consists of four essential steps: (1) Planning the review question as well as the criteria that should be met in the target papers, (2) Selecting papers, (3) Analyzing information, and (4) Reporting best evidence results [63]. The first step was to specify the research question: what is the existing research about emissions from wastewater-based biogas? The first search was done in February 2021, using Scopus and Web of Science, two databases that are well-known for the availability of extensive scientific documentation, and their search features allow the user to efficiently narrow down and customize the search.

The following keywords were considered as critical to be included in the title and abstract of the documents: “emissions”, “biogas”, “wastewater”. As such, different keywords strings were used in the preliminary search (Emissions AND “biogas from wastewater”), (Emissions AND biogas AND wastewater), (“biogas production” AND emissions), (“biogas use” AND emissions) and (“emissions from biogas” AND wastewater).

After an evaluation of the results obtained from each combination, the final keyword string selected for the second stage was “emissions AND biogas AND wastewater” since it seemed to provide more papers related to the topic. Next, a set of inclusion criteria were applied. The period covered is between 2010 and 2021 since the focus is on the most recent findings concerning this topic. The type of documents was limited to Original Articles and Reviews written in the English language. Furthermore, the results were refined to include subject areas like Energy, Environmental Sciences, Engineering, Earth and Planetary Sciences, Social Sciences, Multidisciplinary, Decision Sciences and exclude subject areas like Chemistry, Genetics and Molecular Biology, Business Management and Accounting, Immunology and Microbiology. Additional keywords were introduced to further refine the results, and those include anaerobic digestion, biogas, wastewater treatment, greenhouse gases, wastewater, waste water, gas emissions, greenhouse gas, sludge digestion, biogas production. The subject areas included in Web of Science are: Environmental Sciences, Engineering Environmental, Green Sustainable Science Technology, Water Resources, Environmental Studies, Multidisciplinary Sciences, Public Environmental Occupational Health. The excluded ones are Biotechnology Applied Microbiology, Engineering Chemical, Agricultural Engineering, Thermodynamics. In the third stage, a manual title screening was performed to appraise whether a paper was related to biogas emissions assessment. For example, papers that estimated or addressed the greenhouse gas emissions from one or more of the following processes: wastewater treatment, anaerobic digestion, biogas upgrading, cogeneration or digestate management. Thus, papers in which the title indicated a focus on themes such chemistry, biology, medicine and materials science were excluded.

Next, an abstract screening and duplicate removal was completed. The papers that did addressed topics outside of the environmental field and regarding environmental impacts, such as technical feasibility issues, economics, and mechanical processes, were excluded. In the fifth and final stage, full papers screening was performed.

3.2.2. Qualitative content analysis

In the present research, a qualitative content analysis method for the data analysis was adopted. It consisted of classifying the papers according to the research objectives then analyzing data in a descriptive way that allows to interpret and draw conclusions answering those objectives [64]. A deductive approach was followed to analyze the articles and decide the main focus of this review based on the main common themes in the papers. The deductive approach, also known as concept-driven, allows assessing the collected data and drawing the implications of a theory or a model about the phenomenon under study [64].

3.3. Results and Discussions

After the preliminary search and the completion of the second stage, 3618 papers on Scopus and 297 on Web of Science were found. The inclusion and exclusion criteria resulted in 131 papers from Scopus and 45 papers from Web of Science. Title and abstract screenings resulted in a total of 63 papers from Scopus and 13 from the Web of Science. After full paper screening, 6 papers out of the scope of the study were excluded with the addition of 3 papers from Google Scholar. Finally, 73 papers that make up the subject of this study were selected.

3.3.1. Bibliometric analysis

In figure 2-1, the papers were classified by year and territory of publication. The number of publications per year shows that research about emissions from biogas from wastewater increased in recent years. Almost half of the results (47%) were published in the last four years. This can be explained by the global awareness and increase of the number of policies concerning environmental protection and that governments are focusing more on the environmental impacts of energy generation technologies from fossil fuels or renewable sources [28], [60].

The majority of the publications were from Europe (47% of the total publications with nine papers done in Germany), followed by North America (23%), Asia (17%), Latin America (7%), Oceania (3%) and Africa (1%, with one article. This result may be explained by the fact that Europe is the leader in the installed biogas plant capacity and resource availability to conduct advanced research [65]. For instance, in 2017, the total number of biogas plants in Europe was 17,783 with Germany on top, having 10,791 plants [66]. Furthermore, the main research focus has been on the technology improvement [67], [68]. This background is also indicative of the reason why the majority of the papers done for developed countries' case studies are experimental, while most for developing countries are theoretical or review papers.

The journal *Water Science and Technology* had published 9 papers (Figure 2-2) which is the highest compared to all the other journals followed by the journal *Water Environment Research* with 7 publications which are water research related journals since the present topic concerns biogas produced from wastewater and consequently an important portion of the selected papers studied emissions from wastewater treatment process and facilities.

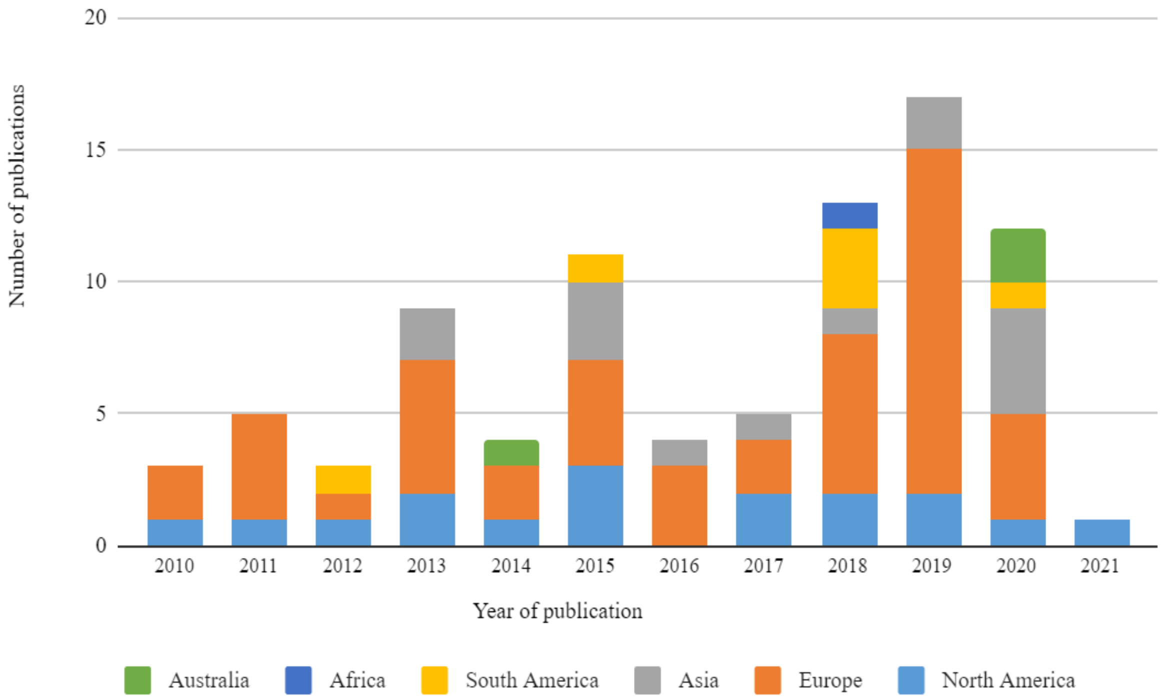

Figure 3- 1: Number of publications per year and per continent

All the journals are environmental science related journals either specialized in water or energy and environment. That is expected since the topic addresses one of the most prominent themes in this field: greenhouse gases emissions therefore the focus during the search and selection of publications was on papers studying the environmental aspect of biogas.

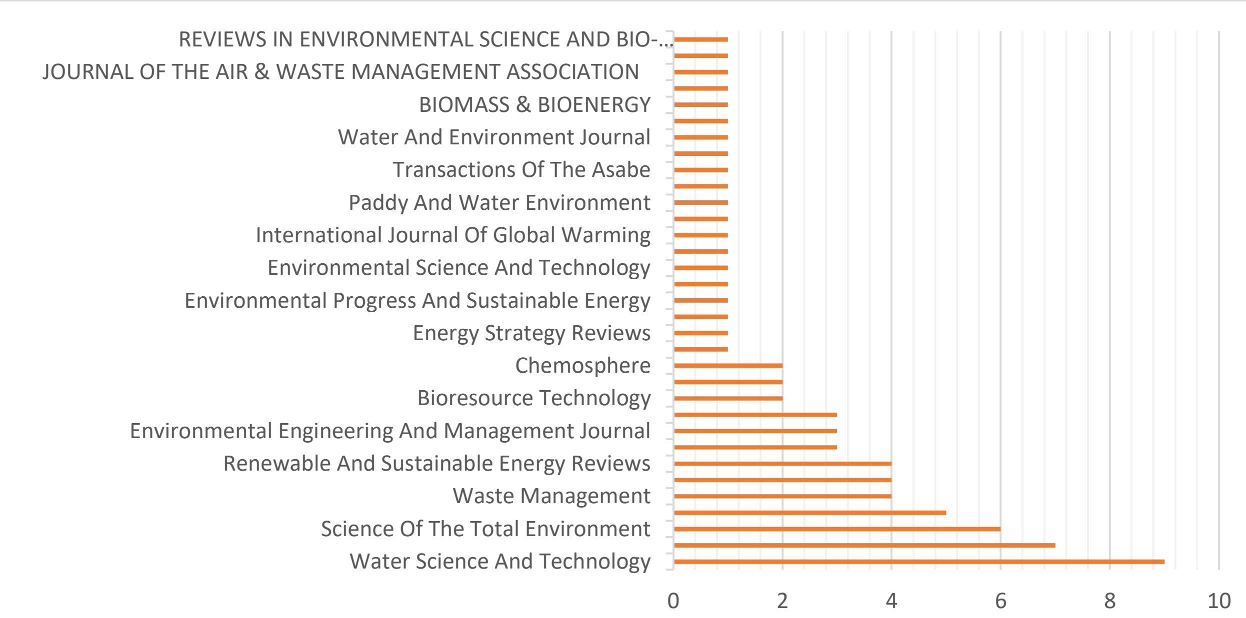

Figure 3- 2: Number of published papers per journal

The keywords map (Figure 2-3) was performed using the software VOSviewer [69]. The sizes of the circles represent the frequency of each keyword and the links between them. The most frequent keywords were respectively emission, biogas, wastewater treatment plant, greenhouse gas emission, sludge, and impact. This result is expected since the topic addresses one of the most prominent themes in the field of biogas: greenhouse gases emissions therefore the focus during the search and selection of publications was on papers studying the environmental aspect of biogas. Particularly, it is also noticeable that the papers selected are focused on methane emissions as well as biogas used for energy production in the form of electricity.

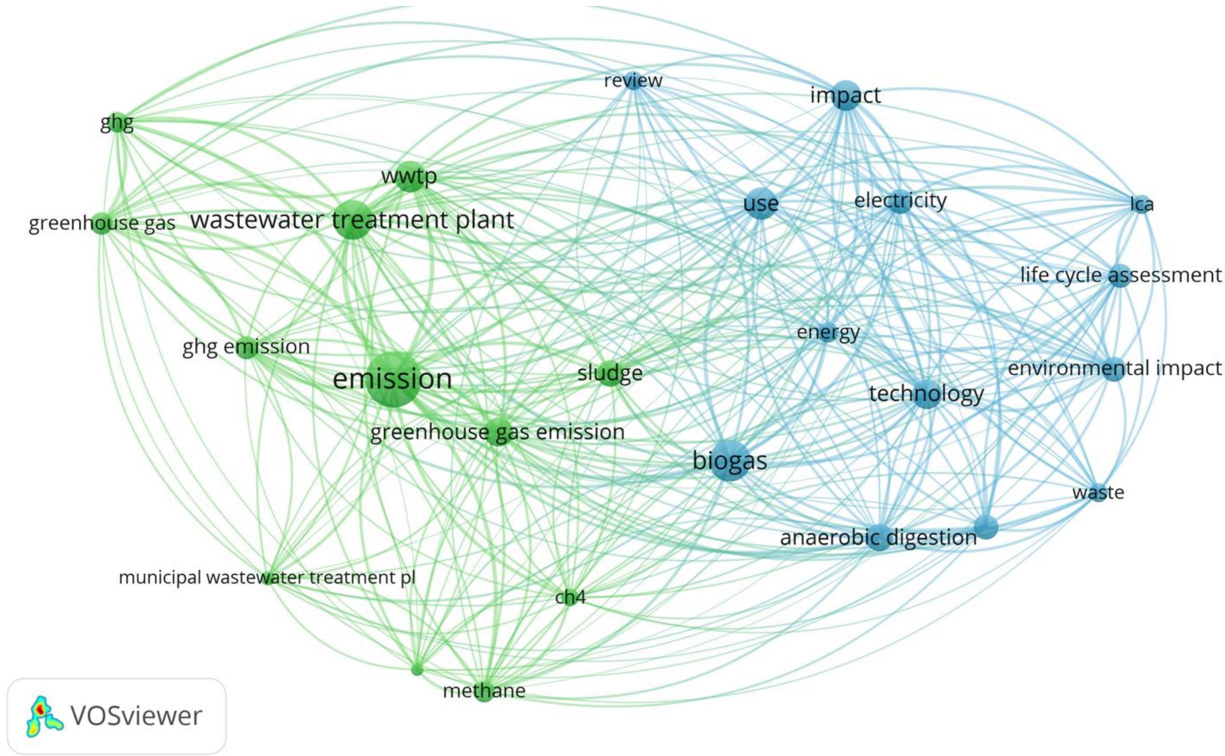

Figure 3- 3: Keywords map on VOSviewer

The most frequent keywords also include those related to wastewater treatment (wastewater treatment plant, sludge, WWTP) which are connected to the focus of the topic: wastewater as feedstock for biogas.

3.3.2. Thematic classification

The current research focuses on emissions from biogas in all its life cycle processes shown in Figure 2-4. A thematic synthesis was used here to classify the papers into three categories: emissions from wastewater treatment (42 papers), emissions from biogas production and use (31 papers), and emissions from other processes (11 papers).

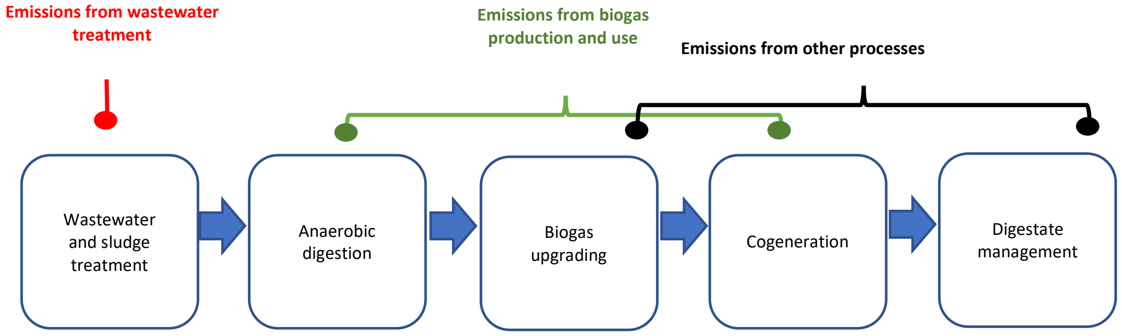

Figure 3- 4: Biogas processes and categories

Wastewater treatment is the first process of the biogas life cycle and can also be called feedstock production, which is an important process in the biogas life cycle; therefore, it should be studied thoroughly. Several papers about emissions from wastewater treatment were selected [70]–[72]. While some of the papers consider anaerobic digestion in the treatment process, there were no emissions estimations from the process itself [29], [73]. Therefore, a second category is considered for articles treating emissions from anaerobic digestion (production) and cogeneration (use) in general. The third category, emissions from other processes, includes biogas upgrading (cleaning) and digestate management.

Based on the categories, information about sources of emissions, estimation methods, and impact categories will be the main focus of this systematic review.

3.3.3. Sources of emissions

- Emissions from wastewater and sludge treatment

Most of the selected papers classified emissions from wastewater treatment into two categories: on-site (or direct) and off-site (or indirect) emissions.

On-site emissions include GHG emitted from the processes directly related to the wastewater treatment line in the plant. Off-site emissions include emissions indirectly related to the activity of the plant and external activities. Liquid treatment processes and fossil fuels combustion are the sources of on-site GHG emissions while production and transportation of electricity, fuels, and chemicals for on-site use, as well as digestate composting and degradation of residual constituents in the WWTP's effluent to rivers, are the primary sources of off-site emissions [70]. Kyung et al. (2015) described on-site emissions as GHG emitted during wastewater treatment, sludge digestion, and system maintenance. He found that dissolved and accumulated GHGs released by air blowing from the aeration tank are the major source of on-site emissions, while chemical production is the main source for off-site emissions [72]. The Thickener, buffering tank for sludge treatment are also on-site emission sources [67].

- Emissions from biogas production and use

The counting of emissions from plants that produce and use biogas is sometimes a conflicting point. For example, while CO_2 emitted from biogas combustion is usually not counted [74], Lobato et al. (2012) considered combined heat and power plant (CHP), also called cogeneration, and flare as main sources of on-site emissions. He also considered the loss of CH_4 dissolved in the effluent or in the waste gas from the chemical oxygen demand (COD) in wastewater as a significant source of emissions [75].

Compared to traditional WWTPs, those equipped with a biogas production unit had an increase in the volume of treated sludge generated and its disposal issues [29]. There are other emission sources like broken digester caps, leaky gas valves as well as leakages in the digester, and abandoned biogas projects that can be a source of aquatic and atmospheric pollution [37]. Methane emissions can also occur due to incomplete combustion or biomass storage prior to anaerobic digestion [60].

- Emissions from other processes

The products of anaerobic digestion are raw biogas and digestate. Raw biogas needs further cleaning to remove impurities such as CO_2, Hydrogen sulfide (H_2S), water (H_2O), and siloxanes and increase its methane content not only when it will be injected into the gas network, but also before its use for CHP [76]. These impurities can cause corrosion and damage the CHP engine and become a source of potential hazards if they are not removed from the biogas [77].

There are various technologies for biogas upgrading: physical absorption (water scrubbing), chemical absorption (amine wash), pressure swing adsorption, Bottom Ash for Biogas Upgrading (BABIU) process [76], [78]. They vary with the requirements of the final biogas use [77]. These technologies may also be a source of emissions [76], [78]. In a study by Kvist et al. (2019), there were variable CH_4 losses that can reach up to 1.97% from water scrubber, and amine-based technologies had the least CH_4 loss compared to the other technologies [76]. The two primary emission sources from high pressure water scrubbing are exhaust gas from the desorption columns and indirect emissions from energy consumption [79]. In another study, different biogas upgrading technologies for biogas feeding to the gas grid were assessed. The BABIU technology was compared to other technologies (membrane separation, pressure swing adsorption, water scrubbing) in terms of emissions. BABIU was the one with the most negligible impact [78].

The second product of anaerobic digestion is digestate. It is the remaining slurry of the initial sludge after chemical biodegradation. Digestate is very rich in nitrogen and potassium, which makes it good enough to replace chemical fertilizers. It represents an important source of emissions if not disposed of properly. According to Nakamura et al. (2014), the digestate from livestock wastewater anaerobic digestion in Japan sometimes needs to be discharged to rivers because farmers do not have enough land to apply it. The major source of GHG emissions from digestate is the transportation from the treatment plant to the application field, which accounts for 67% of the total emissions [80]. However, it is also less likely to store considerable amounts of digestate for a long time, and thus, it becomes a source for air and water pollution. In a comparison of four digestate use scenarios, digestate directly applied to farmland was the best scenario in case of the absence of its transportation [81].

As mentioned before, emissions from the biogas life cycle can occur from different sources in each process, depending on the layout of the plant and the various treatments used. This shows that the more processes considered, the more emissions there will be. Usually, the most complex process is wastewater treatment that should go through different settling tanks and biological treatments to extract the sludge used as feedstock for the anaerobic digestion. For that reason, some plants used technologies combining different processes in order to avoid more emissions. Upflow anaerobic sludge blanket (UASB) is one of these technologies that combine wastewater treatment and anaerobic digestion and limit the emissions problem [75], [82].

Additionally, even though there is an agreement on the two main categories of emissions (on-site and off-site), there is a difference in the approaches to decide the sources that should be included in the emissions balance sheet as well as the results obtained.

Moreover, there is a variation in the considered emissions, although there is agreement that CH_4 is the common GHG emitted. For example, according to the Intergovernmental Panel on Climate Change (IPCC), CO_2 production from biogenic sources should not be considered as GHG emissions, and consequently, emissions from cogeneration exhaust gases are usually not counted while other studies counted those emissions.

Lastly, in the previous studies of biogas emissions, biogas upgrading was usually neglected for the emissions estimation. There are some studies about emissions from biogas upgrading separately from the rest of the processes [76], [78], [79]. Usually, the studies about emissions from biogas upgrading concern biogas for gas networks and not biogas for cogeneration as a use pathway [83]. Hence, emissions from biogas upgrading need to be more considered for the future emission estimations.

3.3.4. GHG estimation methods

- Estimation for wastewater and sludge treatment

One of the most common methods to estimate emissions from wastewater treatment is carbon footprint analysis [71], [84]. Maktabifard et al. (2019) performed a carbon footprint analysis for two municipal WWTPs located in northern Poland using an Excel spreadsheet. Data collection was done by a daily wastewater samples collection and analysis in accredited laboratories meeting the Polish standards. Missing data like emission factors were taken from the literature [71].

Several studies used mathematical modeling [70] to estimate emissions from biological treatment processes of on-site and off-site emissions and excluding sludge treatment and chemical manufacturing. Another study estimated emissions using a mathematical model and some on-field measurements using a gas chromatograph equipped with a flame ionization detector for CO_2 and CH_4, and an electron-capture detector for N_2O. Ten yearly GHG sampling and analysis for each gas was done and the results were used as input data to calculate on-site emission factors then to estimate final emissions. The model also developed equations to estimate off-site emissions [72]. Another way to estimate on-site and off-site GHG emissions is Bridle modeling approach [85].

International standards for estimation that provide emission factors based on the literature are usually used in the case of lack of data [86]. One of these standards is IPCC guidelines for national greenhouse gas inventories which is an international method provided by the United Nations to estimate GHG emissions from different sectors including wastewater [74].

There are also other national standards developed by each government but usually only for developed countries [73].

Countries or plants that allocate a budget for the GHG emissions problems, use more experimental methods like on-site measurements using sophisticated and specific tools for such a purpose. One of these methods is tracer dispersion method that allows to detect small CH_4 and N_2O concentration changes [87], [88]. Infrared gas analyzer was also used to measure the methane and nitrous oxide concentration in the off-gas to measure the gas flow rates weekly then calculate methane and nitrous oxides concentrations by multiplying the obtained results by the prevailing flow rate in the off-gas pipes [89]. Demir et al. (2019) measured methane and carbon dioxide emission ratios from on-site activities using an emission isolation flux chamber and a portative multi-gas analyzer [90]. Another common method to assess the environmental impacts of any technology is life cycle assessment (LCA) [33], [91], [92].

Some authors combined different methods to have more accurate results. For instance, to develop a model to estimate emissions based on IPCC guidelines and on-site measurements using a portative gas detector equipped with electrochemical sensors and an internal, high-performance pump and a data logger for CO_2 and CH_4 emissions for the GHG from the UASB reactor [82]. Another study used a combined model of multiple calculation methods (IPCC–2006, WSAA– 2006, LGO– 2008, Bridle- 2008, NGER–2009) for each one of the on-site and off-site emissions since only one method doesn't include all necessary information [93].

- Estimation for biogas production and use

The estimation methods of GHG emissions from biogas production and use are similar to those for wastewater treatment and are also various.

Lobato et al. (2012) used a mathematical model to calculate the COD mass balance. This model calculates emissions taking into account the portion of biogas recovered from the total produced [75].

Most of the methods used for estimation of emissions from wastewater treatment can also be used to estimate emissions from anaerobic digestion and cogeneration such as carbon footprint analysis [36], [94] the tracer gas dispersion method to quantify fugitive methane emissions from the plant. [68], [95], [96]. IPCC guidelines Tier 1 method was also used and compared to the results of on-site measurements using a portable biogas analyzer that allows to measure methane concentrations [97]. Non-dispersive infrared camera was also used with anaerobic digesters then emissions were quantified using the Flux-Chamber method and sampling from the digester's circulation pipe. Gas chromatography-mass spectrometry was used to measure the dissolved methane in the sludge digester [67].

In a study similar to Lobato et al. (2012), Schaum et al. (2015) estimated methane emissions from sludge treatment line, digester and CHP using COD balance. He measured dissolved methane and methane remaining in the digested sludge experimentally while the methane slip was estimated theoretically [98]. One of the studies estimated emissions from the engine using a Bay Area AQMD-certified source tester [99].

- Estimation for other processes

To estimate emissions from biogas upgrading, a study did several gas samplings for biogas that leaves the anaerobic digester, waste gas after biogas upgrading, biomethane after upgrading, and gas after regenerative thermal oxidizer. Then the analysis was made using gas chromatography [76]. Another study used Aspen Plus software [79]. Pertl et al. (2010) used

LCA to estimate emissions and evaluate the environmental impact of different biogas upgrading technologies [78].

Regarding digestate management, Scheutz et al. (2019) studied the emissions from a biogas plant, including transportation of digestate and its substitution for chemical fertilizer using the tracer gas method [95].

The diversity of the methods used to estimate GHG emissions from biogas production and use is one reason for the variation of the results. This diversity is due to the availability of resources that need to be invested and the priority of the emission problem for the plants or countries. Foremost, from an economic point of view, biogas employment for large scale production has a relatively high initial cost for a low efficiency return which makes low-income countries less prone to invest in this kind of projects especially in the rural areas [100]. For example, while Germany has the highest number of large-scale digesters in the world, India, a country that generates huge amounts of wastewater is only able to install small scale digesters. For developing countries, the lack of governmental policies encouraging the production of biogas by allocating a budget for that is the main inhibiting factor [39]. Consequently, even countries that decide to start producing biogas are less likely to initially consider limiting the emissions from the plant.

The availability of data is also an important problem for emissions quantification. The use of a combination of different methods in this context may lead to least uncertainties and more accuracy.

3.3.5. Environmental impact categories of biogas

One of the factors that help understand the current attitude towards biogas from wastewater is to identify its impacts on the environment and its gravity. LCA is one of the methods that are used to identify the environmental impact categories of a product in all the stages of its life cycle and starting from its raw material coming to its waste [101].

Many of the papers in this review that assesses the production and use of biogas are LCA studies [28], [29], [81], [91], [92], [102]–[105].

Usually, the studies follow the guidelines of ISO 14040 and ISO 14044 that regularize the principles of LCA studies [29], [81], [103]–[105].

The general goal of the LCA studies is to assess the impact of biogas on the environment by quantifying GHG emissions, identifying their impacts on the environment and trying to find solutions to reduce them [106]. Additionally, each study has different boundaries, assumptions and limitations that should be mentioned and explained [103]. Regarding biogas boundaries, this study considers the system from the feedstock production until the products use and byproducts disposal.

One of the basis of an LCA study is the choice of the functional unit which is the scale with which data will be presented in the inventory [91]. The functional unit may differ from a study to another even if they have the same goal. Most of the used functional units are: PE (population equivalent) [29], 1 MJ equivalent of NG energy at the consumer gate [92], 1 m^3 of biogas (production or utilization) [103], 1 t of feedstock; 1 t of digestate; 1 MWh of electricity produced [104].

The most commonly used software for LCA performance is SimaPro (different versions). The most used database is Ecoinvent (integrated in the software SimaPro) [29], [104].

- Impact categories

The third step in every LCA study is life cycle impact assessment (LCIA), a method that defines the areas of impacts targeted in the study then measure their intensity based on the inventory data to make the environmental assessment of the technology [102]. The LCIA is a more clear way to present data of the inventory analysis in the form of a limited number of indicators allowing to show the severity of the impact on the environment [29], [92]. These indicators should be chosen based on scientific evidence [28]. For example, since the data of emissions from biogas are the quantities of CO_2, CH_4, and N_2O, these numbers should be converted into one specific indicator that allows the comparison and which is CO_2 equivalence. The results can then be easily interpreted. The most common life cycle impact assessment methods and tools used are: ReCiPe v.1.08 method [29], IMPACT 2000+ method [92], ReCiPe Endpoint & ReCiPe Midpoint [104], Eco-indicator 99, CML [79].

According to Meneses-Jácome et al. (2015), global warming potential, climate change, human health, acidification and eutrophication potentials are the most affected categories for biogas produced from wastewater [92]. Other studies also confirmed that and included other impact categories like photochemical ozone creation potential, ecosystems, particulate matter formation, resource consumption, ozone depletion [104], [106].

Air emissions and electricity are the main reason why climate change is the category usually presenting the highest damage [29]. Composting and storage of digestate also highly affect the climate change category [81]. CH_4 emissions from cogeneration and nitrous oxide emissions from the use of digestate as fertilizer are the most responsible processes for global warming potential [105]. The use of digestate to replace chemical fertilizer increased the freshwater eutrophication impact category due to phosphorus release to groundwater [103]. Fuel combustion is causing nitrous oxide emissions to contribute to the over-fertilization and increasing acidification and eutrophication potentials [105]. Digestate storage and transportation are the main contributors to the human health impact category as well as resource consumption, particulate matter formation, and ecosystems because of the high emissions of methane and ammonia [81], [104]. Emissions from anaerobic digestion as well are major contributors to human health and ecosystems.

3.4. Conclusion

This topic was done in order to clarify the current situation of research of emissions from biogas produced from wastewater. A systematic review was conducted to collect all the relevant papers related to this topic then analyze them. Emissions from biogas can occur in the different steps of the lifecycle especially in the aerobic processes (aeration tanks) for wastewater treatment as well as electricity supply of the plant from fossil fuels. Anaerobic digestion is also marked by emissions due to poorly maintained digesters. Carbon dioxide and carbon monoxide emissions from the biogas combustion cogeneration plant are also an important source of emissions. Regarding biogas upgrading, water scrubber was identified as the technology with the highest impact on the environment as well as composting as a digestate management option. Authors used different methodologies to estimate emissions using international standards, countries guidelines, experimental methods, mathematical models, etc. One of the most used methods was LCA for its ability to elaborate a reliable assessment of technologies on different categories. The highest impact of biogas production and use from wastewater was on climate change, global warming, and human health.

This topic allowed to know the existing research related to emissions from biogas from wastewater so that future research paths will be built on this basis in order to try to improve this field. It also highlighted the areas of study in the literature and showed the ones that need further research. Consequently, in the next chapter, the case study of Tunisia is presented.

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

4.1. 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 [107], [108]. 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 [109], [110]. The most endangered region from water scarcity currently is the MENA region, and it is the most exposed and vulnerable to the impacts of climate change [111]–[113]. Tunisia is one of the MENA countries characterized as an arid country currently in danger of water stress [114].

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 [115]. The generated sludge can be exploited to produce two types of energy- electricity and heat, which can reduce the WWTPs needs for electricity from fossil fuels and, therefore, contribute to solving the ongoing electricity demand requirements [116], [117]. 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 [41].

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 and then extend biogas production to all the WWTPs [118]. In 2017, Tunisia had a connection rate to WWTPs of 86.1%, 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 [43].

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 [44]. 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 [119]. A preliminary study about biogas in Tunisia predicted that the amount of sludge produced in 2030 would be 151.131 thousand tons, equivalent to 90,798.13 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 [119], [120]. 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 [121].

Despite the anticipated benefits of wastewater treatment and valorization, biogas technology can cause considerable emissions of GHGs, notably CH_4, CO_2, and N_2O in the wastewater treatment process and during the biogas production and use [28], [106], [122], [123]. 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% [45]. 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 $ktCO_{2eq}$ in 2020 and 815 $ktCO_{2eq}$ in 2030 [121]. 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 [123]. For example, Blanco et al. (2016), Tauber et al. (2019), and Szabo et al. (2014) quantified emissions from WWTPs in Spain, Austria, and Hungary [29], [36], [67]. However, few estimated emissions from biogas use in upper-middle-income countries, and none were found in lower-middle-income countries [123]. 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) [92], [97]. 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 [124].

Therefore, this topic 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 profile. 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.

4.2. Gafsa Wastewater Treatment Plant

Biogas production is not a widespread technology in Tunisia and is just starting in some industries such as WWTPs [120]. The three existing digesters in 3 different WWTPs are no longer working [119].

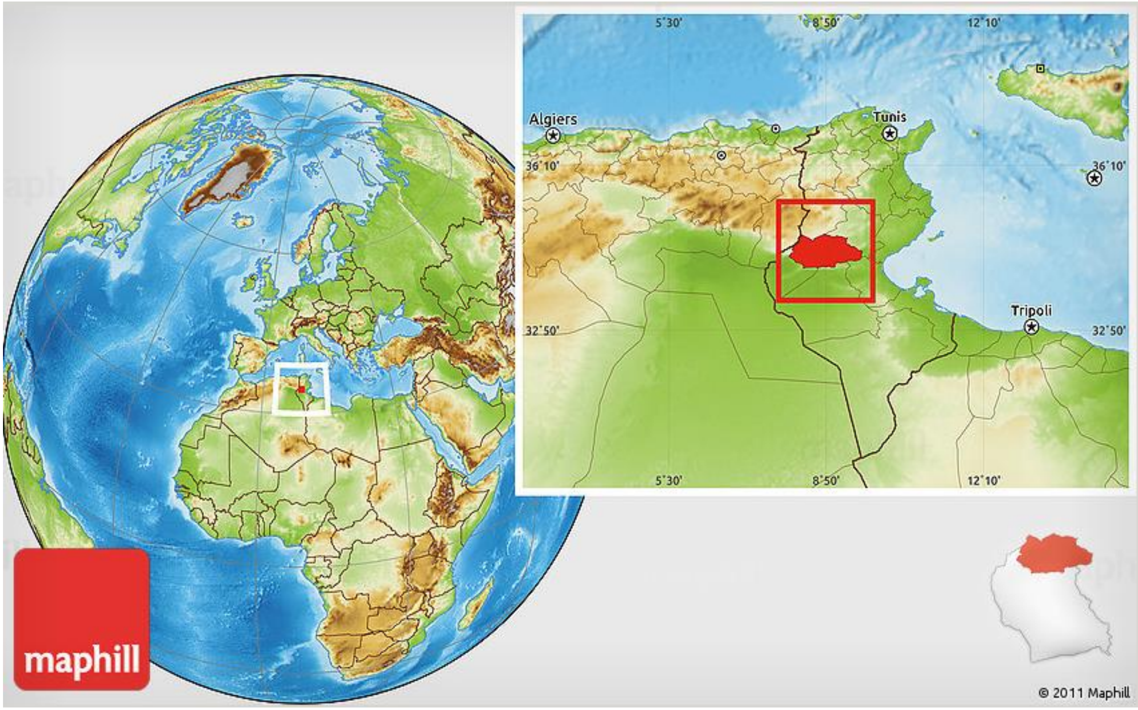

Figure 4- 1: Location of Tunisia and Gafsa (in red)[125]

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 4-1). 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 4-2,3). Therefore, this study will focus on the Gafsa WWTP for emissions estimation as a reference facility for the whole country.

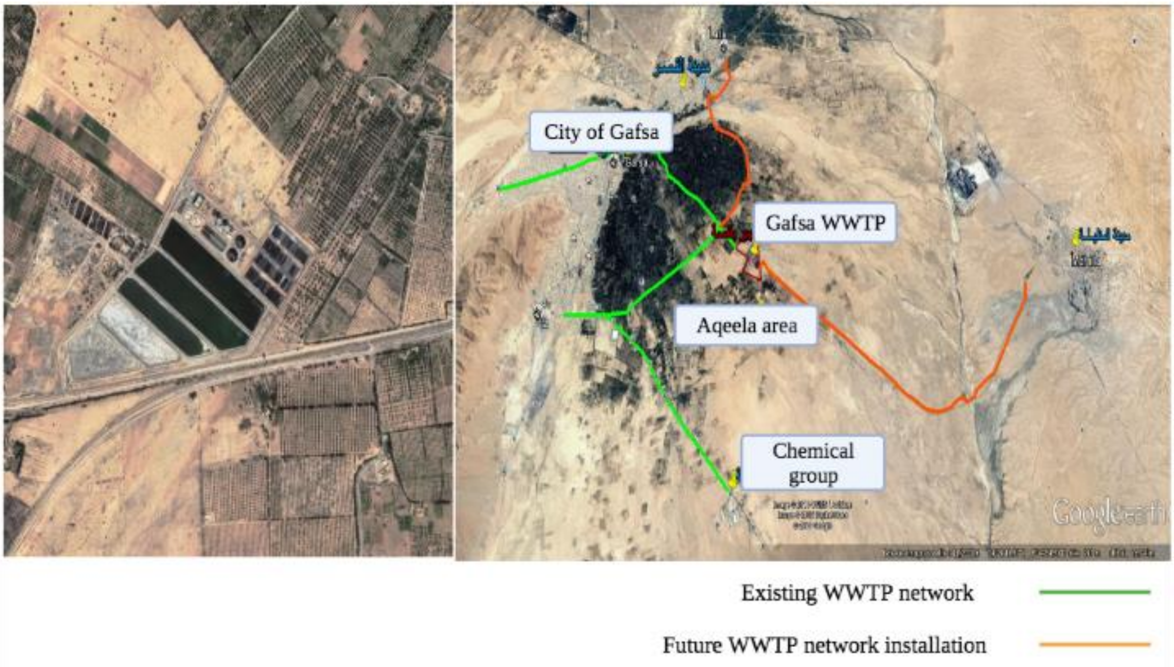

Figure 4- 2: Location of Gafsa WWTP and its connected areas[126]

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 9,091 kg/day and 8,278 kg/day. The plant is equipped with two anaerobic digesters and two cogeneration engines. The volume of each digester is 2,746 $m^{3,}$ and the expected production of biogas per day is about 3,350 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 kW, and the thermal power is 424 kWth. For this purpose, two cogenerators with hourly consumption, each 110 Nm^3/h, were installed.

Figure 4- 3: Gafsa WWTP after rehabilitation and anaerobic digesters installation [126]

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.

Table 4- 1: Input and output wastewater characteristics

	Input wastewater	**Output wastewater**
BOD5 (mg/l)	587	23
COD (mg/l)	1,206	86
Suspended solids (mg/l)	542	25
Total Organics in wastewater (kg BOD/day)	6,098	243

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. Table 4-1 presents the wastewater treatment indicators in Gafsa WWTP. Figure A1 in supplementary material presents a schematic overview of the process at Gafsa WWTP, from wastewater treatment to biogas production.

4.3. Materials and methods

In a previous study by the authors, a systematic review was conducted, and several methods for emissions estimation were identified [123]. Based on that, three previous studies that used estimation methods specific to each process were selected as the basis for this study [70], [74], [93]. 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. IPCC guidelines, 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 [70], [74], [93], [127], [128].

Specifically, IPCC guidelines are one of the main references for calculation of emissions from the different sectors including wastewater treatment and discharge. It provides detailed approaches based on the data availability and covers the different aerobic and anaerobic processes emissions [74].

Regarding the emission sources considered in the emissions counting in this research, the selection of processes was based on the mode of operation of the Gafsa WWTP and the data availability.

It was assumed that the plant operates 365 days every year for the annual emissions calculation. The system boundaries of this research are presented in the figure 4-4.

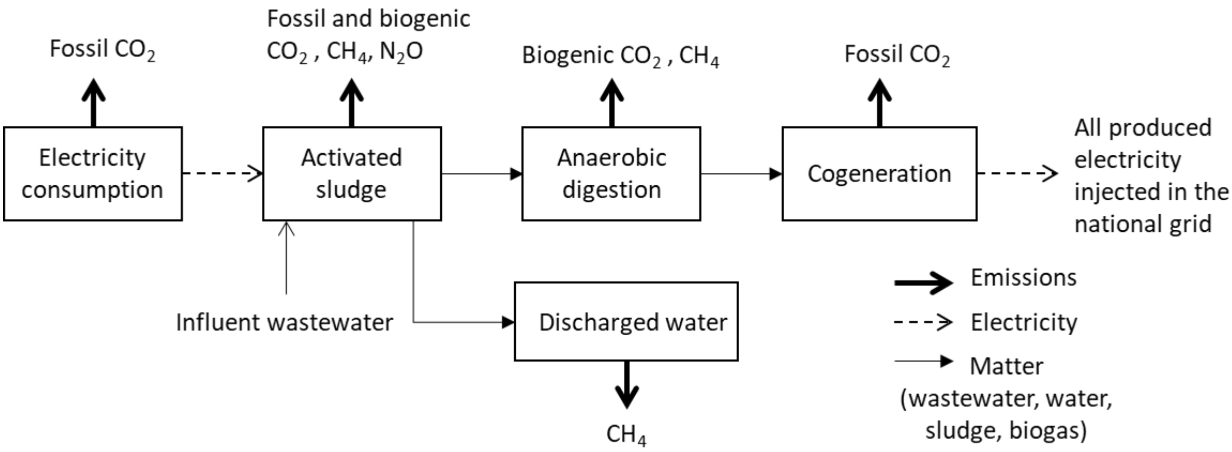

Figure 4- 4: System boundaries and processes included without auto-electricity supply (case 1)

Only emissions from external electricity consumption (fossil CO_2) were counted for the off-site or indirect emissions since data about chemicals use and transportation are unavailable. Additionally, under the current situation in Tunisia, the produced electricity by cogeneration will all be injected into the national grid and therefore all the electricity needed by the WWTP is produced from fossil fuels. 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. According to IPCC, CO_2 emissions during wastewater treatment by activated sludge (aerobic treatment) and anaerobic digestion are considered from biogenic source and therefore not included in the reporting of the total emissions. However, fossil carbon in wastewater can cause fossil CO_2 emissions during wastewater treatment. This fossil CO_2 is derived from the use of petroleum-based products like pharmaceuticals, cosmetics, detergents, etc. [1]. Hence, the amount of fossil carbon in wastewater can be high (could reach up to 14 %) causing significant non-biogenic emissions [2]. However, there is no method defined yet by IPCC to calculate those emissions other than on-site measurements [3]. Therefore, CO_2 emissions from activated sludge and anaerobic digestion are not calculated in this research.

The other considered emissions are CH_4 emissions from activated sludge, anaerobic digestion and discharged water and CO_2 emissions from cogeneration and N_2O emissions of all the plant.

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 [129]. Most recent found data have been used, and estimations were made for the year 2021.

A second case was considered in which all the electricity produced by cogeneration is used to cover the plant's needs and the rest of electricity is taken from the grid. In this case, the potential electricity production by cogeneration is calculated based on the provided characteristics of the cogeneration engine and the amount of produced methane. Figure 4-5 shows the emissions sources included in this case.

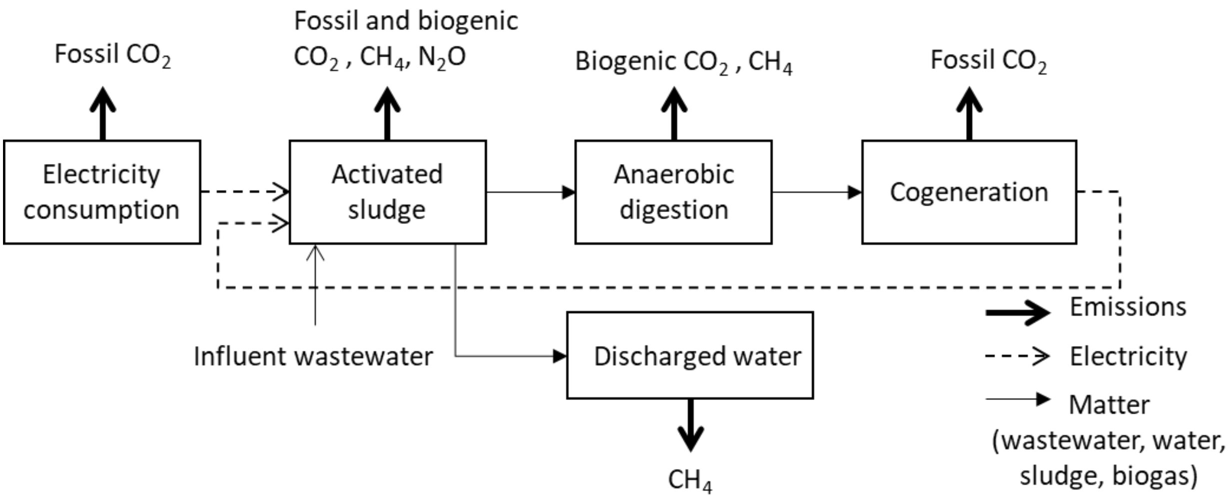

Figure 4- 5: System boundaries and processes included with auto-electricity supply (case 2)

4.3.1. Emissions from electricity consumption

A WWTP needs electricity to operate, for instance, for the building lighting, for specific processes such as 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 [130].

Emissions from electricity consumption are generally calculated by multiplying the quantity of electricity consumed by the adequate emission factor [93], [131]. The CO_2 off-site emissions from electricity were calculated as follows:

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

(4-1)

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 (kWh/year)

EF_{elect}: the annual average of CO_{2eq} emission factor for the electricity in the year (gCO_{2eq}/kWh)

4.3.2. Emissions from activated sludge

The activated sludge process is the most energy-intensive and associated with actual emissions in the centralized wastewater treatment (in WWTPs) [132]. The transportation of wastewater to treatment plants in closed sewers and the high content in organic matter and the stagnation state in some processes and the existence of suitable conditions for anaerobic digestion like warm temperatures may all accelerate the degradation of matter and enhance the formation of CH_4 emitted to the atmosphere uncontrollably.

Following are the steps to estimate CH_4 emissions from activated sludge process according to IPCC guidelines [74]. These steps can be applied also for the estimation of CH_4 emissions from discharged water.

1. CH_4 emission factor for wastewater treatment:

$$EF = B_0 \times MCF$$

(4-2)

Where:

EF= emission factor, kg CH_4/kg BOD (0.018 default)

B_0= maximum CH_4 producing capacity, kg CH_4/kg BOD (0.6 kg CH_4/kg BOD)

MCF= methane correction factor (fraction) (= 0.03 default)

2. CH_4 emissions from wastewater for activated sludge process:

$$CH_{4actslu} = [(TOW - S) \times EF] - R$$

(4-3)

Where:

$CH_{4actslu}$= CH_4 emissions from activated sludge, in inventory year, kg CH_4/year

TOW= organics in wastewater of activated sludge, in inventory year, kg BOD/year

S= organic component removed from wastewater (in the form of sludge) during activated sludge process, in inventory year, kg BOD/year

EF= emission factor for activated sludge, kg CH_4/kg BOD

R= amount of CH_4 recovered from activated sludge, in inventory year, kg CH_4/year. Default value is zero.

IPCC guidelines provided equations to estimate TOW and S. However, in this research, the total organics in wastewater in activated sludge process TOW= 2,225,770 kg BOD/year and the organic component removed from wastewater during activated sludge process S= 2,137,075 kg BOD/year were provided by Gafsa WWTP. The recovery of methane is after the anaerobic digestion process in this case and no recovery from activated sludge emissions and consequently R=0.

4.3.3. Emissions from the anaerobic digester

There are fugitive CH_4 emissions from the digester especially in the poorly managed plants. The produced CH_4 that is combusted in the cogeneration plant is subtracted in the estimation equation of IPCC guidelines. CH_4 emissions from anaerobic digestion are calculated according to IPCC guidelines [133]:

$$\mathrm{CH}_{4\mathrm{anadig}} = (\mathrm{M} \times \mathrm{EF}) - \mathrm{R} \tag{4-4}$$

Where:

CH_4 Emissions = total CH_4 emissions in inventory year, kg CH_4/year

M = mass of organic waste treated by anaerobic digestion, kg BOD/year

EF = emission factor for anaerobic digestion, kg CH_4/kg (=0.8 g CH_4/kg)

R = total amount of CH_4 recovered in inventory year, kg CH_4. The amount of recovered methane is considered in the above emission factor and therefore R = 0.

The mass of organic waste treated by anaerobic digestion is equivalent to the mass of organic waste removed from activated sludge process and therefore, M = S.

4.3.4. Emissions from discharged water

In Tunisia, treated wastewater is discharged into aquatic environments. The efficiency of the treatment process reflects the quality of discharged wastewater and its possible related emissions.

The calculation's steps are the same as in 4.3.2. However, TOW is replaced by $TOW_{effluent}$= 88,695 kg BOD/year = total organics in the treated wastewater effluent discharged to aquatic environments in inventory year, kg BOD/year. $TOW_{effluent}$ was provided by Gafsa WWTP. Additionally, for the calculation of emission factor from discharged water: MCF = 0.11; EF = 0.068 kg CH_4/kg BOD.

4.3.5. 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 [70]:

$$CO_{2cog} = (2.75 \times CH_{4prod}) \tag{4-5}$$

Where:

CO_{2cog}: mass of CO_2 production by CH_4 combustion (kg CO_2/day)

CH_{4prod}: mass of CH_4 production (kg CH_4/day). It was assumed in this research that the treatment by anaerobic digestion reduces 50% of the organic component amount and that the methane production yield is equivalent to 0.35 under suitable reaction conditions [134], [135].

4.3.5. Nitrous oxide emissions

Wastewater and wastewater-related activities are the fifth major contributor to worldwide N_2O emissions [136]. 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 [137]–[141]. However, no field measurement or specific method can be used in this research because of a lack of data. Therefore, N_2O emissions of all the plant were calculated using the IPCC method for domestic wastewater [74]:

$$N_2O_{plant} = (U \times T \times EF) \times TN \times (44/28) \tag{4-6}$$

Where:

N_2O_{Plant} = N_2O emissions from domestic wastewater treatment plants in inventory year, kg N_2O/year

TN = total nitrogen in domestic wastewater in inventory year, kg N/year

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 [142].

4.3.6. 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}) [74].

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 wider groups than those of the study area [143]. 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 [144]. 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 6.47 million inhabitants in 2018 [145]. Currently, the WWTP of Gafsa serves 184,000 inhabitants.

$$\text{Emissions}_{\text{country}} = (\text{Emissions}_{\text{GafsaWWTP}} \div 184000) \times 6470000 \tag{4-7}$$

Table 4-2 presents 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 appendix A.

Table 4- 2: Input data sources and values

Process	Variable	Value	Source/Reference
Electricity consumption	C_{elect} (KWh/year) (case 1)	1,924,286	[129]
	C_{elect} (KWh/year) (case 2)	252,209	[129]
	EF_{elect} (gCO_{2eq}/kWh)	0.57	[146]
Activated sludge	TOW (kg BOD/year)	2,225,770	[129]
	EF (kg CH_4/kg)	0.018	[74]
	$S_{aerobic}$/ M	2,137,075	[129]
Anaerobic digestion	EF (kg CH_4/kg)	0.0008[70][70]	[133]
Water discharge	$TOW_{effluent}$ (kg BOD/year)	88,695	[129]
	EF (kg CH_4/kg)	8.068	[74]
Cogeneration	CH_{4prod} (kg CH_4/day)	373,988	[129]
Nitrous oxide emissions	annual per capita protein supply	36.13	[142]
	T	0.34	[74]
	EF (kg N_2O-N/kg N)	0.016	[74]
	U	0.34	[74]

4.3.7. 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 [147]. 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 [148]. Sensitivity analysis allows predicting the output depending on the input data variation [147], [149]. In general, for a mathematical model in the following form:

$$Y = Z(X) \tag{4-8}$$

Sensitivity analysis is calculated as follows [150]:

$$Si = \frac{\partial Z(X)}{\partial Xi} \tag{4-9}$$

In this research, the sensitivity analysis focused on the processes with direct emissions: N_2O emissions from wastewater treatment and CH_4 from activated sludge and anaerobic digestion processes. 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 total nitrogen in domestic wastewater (TN), total organics in wastewater (TOW) and organic component removed from wastewater after activated sludge process ($S_{aerobic}$=M). The effect of these parameters on the emissions was then plotted.

4.4. Results and Discussions

4.4.1. 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 4-3.

Table 4- 3: Emissions amount of Gafsa WWTP and Tunisia (kt CO_{2eq})

Process	**Case 1**						**Case 2**					
	Gafsa			**All Tunisia**			**Gafsa**			**All Tunisia**		
	CO_2	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**
Off-site electricity	**0**	**-**	**-**	**0**	**-**	**-**	**0**	**-**	**-**	**0**	**-**	**-**
	1.10			**38.57**			**0.14**			**5.05**		
Activated sludge	**-**	**0.04**	**-**	**-**	**1.40**	**-**	**-**	**0.04**	**-**	**-**	**1.40**	**-**
Anaerobic digestion	**-**	**0.04**	**-**	**-**	**1.50**	**-**	**-**	**0.04**	**-**	**-**	**1.50**	**-**
Discharged water	**-**	**0.15**	**-**	**-**	**5.30**	**-**	**-**	**0.15**	**-**	**-**	**5.30**	**-**
Cogeneration	**0**	**-**	**-**	**0**	**-**	**-**	**0**	**-**	**-**	**0**	**-**	**-**
	1.03			**36.16**			**1.03**			**36.16**		
Nitrous oxide emissions			**1.24**			**43.65**			**1.24**			**43.65**
Total emissions	**1.47**			**51.86**			**1.47**			**51.86**		
	3.60			**126.59**			**2.65**			**93.08**		

Note: For Off-site electricity and Cogeneration, the upper value is according to IPCC methodology and the lower value is calculated using the methods described in 4.3.1. and 4.3.5.

-: Not applicable

Focusing on Case 1 results, the annual total emissions of Gafsa WWTP were 3.60 kt CO_{2eq}, and the country's emissions were 126.59 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 these results can be underestimated since emissions from wastewater treatment are continuously increasing even with the introduction of biogas and cogeneration technologies to reduce the WWTP carbon footprint [84].

The increase in emissions is also predictable because of 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 [48]. 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 and limited financial resources to cover waste and wastewater management costs [151].

N_2O emissions from wastewater treatment by activated sludge were in 43.65 kt CO_{2eq} representing 34% of the total emissions, making it the highest source of emissions [74]. A report about national emissions in 2012 revealed that N_2O emissions represent 98% of the total emissions of the waste sector [152]. Those emissions can occur because nitrification and denitrification occur in different processes in the plant, especially during the activated sludge process [153]. 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 [138], [140]. Additionally, N_2O emissions would be even higher if emissions from sludge landfilling process were considered in the calculation. Sludge landfilling is one of the most harmful and significant N_2O emissions sources in the field of waste management [154]. Unfortunately, it is also still the most used technique for sludge disposal in Tunisia. 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 [155].

The country's prospected emissions from electricity consumption were 38.57 kt CO_{2eq} which were the second-highest emissions (30%). 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 [29], [71]. In Tunisia, all the electricity from renewable energies is injected into the national electricity grid since there is one monopole company responsible for the production, transport, and distribution of the electricity in Tunisia. Therefore all the electricity consumption of the WWTP should be taken from the grid [156]. 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 [28].

Emissions from cogeneration were 38.57 kt CO_{2eq} representing 30% 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 [77]. Cogeneration engines with higher capacity can also have less carbon footprint than the small ones [94]. Therefore, by enhancing the thermal and electrical efficiency of cogeneration engines, emissions to the air can be reduced [28], [77].

CH_4 emissions from water discharge into aquatic environments were 5.30 kt CO_{2eq} representing 4% of the total emissions. Wastewater effluent is rich in dissolved GHGs that can be released in waterways that are rich with nutrients [157]. 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 [127].

The CH_4 emissions from anaerobic digestion were 1.50 kt CO_{2eq} representing 1% of the total emissions. 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. 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 [67]. Potential CH_4 emissions can be higher if another estimation method was used. 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 [75]. Another research expresses the previous sources of CH_4 emissions degraded inside the reactor [70]. To minimize emissions from anaerobic digestion, checking and maintenance of the digester for leakages should be done regularly [28].

CH_4 emissions from the activated sludge process were 1.40 kt CO_{2eq} and were the least-highest source of emissions (1%). In this step, the air blowing during the dissolution of organic matter in the aerated tank is responsible for these emissions [72]. In Tunisia, activated sludge is the most used process for secondary wastewater treatment besides settling tanks [158]. 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 [159], [160]. In this research, only CH_4 and N_2O emissions from activated sludge have been calculated; however, other studies suggested that there are also other emissions such as hydrogen sulfide, and methyl mercaptan, but there is no applicable estimation method for this research [161], [162].

Following IPCC guidelines, zero emissions from off-site electricity and cogeneration are considered which can drop the total emissions to less than the half from 3.60 kt CO_{2eq} to 1.47 kt CO_{2eq} for Gafsa and from 126.59 kt CO_{2eq} to 51.86 kt CO_{2eq} for all Tunisia. However, in this research, we chose to include the previously cited emission sources for more realistic results.

The total share of CO_2 emissions from wastewater treatment and biogas production nationwide amounted to 74.73 kt CO_{2eq}. Moreover, the total contribution from CH_4 and N_2O emissions were 8.21 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 3,543 kt CO_{2eq} [45]. 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.

4.4.2. Results of the emissions in the case 2

Currently, some revisions of renewable energy laws are starting to be put into action. These law texts state that industries are allowed to produce electricity internally for self-use but still need to be connected to the national grid so that the main company can manage national produced electricity. The emissions in the case where the electricity produced by cogeneration is used internally to cover the plant's needs and the rest is taken from the grid were calculated as in 4.3.1. and the results are presented in Table 4-3 (Case 2).

The cogeneration engine can produce 1,672,078 kWh from the produced methane which means 252,209 kWh is taken from the grid. In this case, the emissions from fossil electricity consumption are 5.05 kt CO_{2eq} representing 5 % of the total emissions. The share of nitrous oxide emissions is 47 %, 39 % from cogeneration, 6 % from discharged water and 2 % from activated sludge and anaerobic digestion of the total emissions. Therefore, by using its own produced electricity, the WWTP can reduce emissions from fossil electricity consumption by 33.52 kt CO_{2eq} (from 38.57 kt CO_{2eq} to 5.05 kt CO_{2eq}). This option will also help reducing the amount of money spent on electricity bills. Hence, encouraging auto-consumption is beneficial both environmentally and economically. It also eases the energy burden on the government and the monopole electricity producer in the country by being self-sufficient in terms of electricity. WWTPs can even increase their electricity production in the future to cover all their needs and sell the surplus electricity to the national grid making anaerobic digestion and cogeneration a source of income.

4.4.3. Sensitivity analysis

Sensitivity analysis of N_2O emissions from wastewater treatment and CH_4 emissions from activated sludge and 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 TOW (Figure 4-6 (a)). However, for the variation of $S_{aerobic}$ inversely influence the emissions from the same process in the same

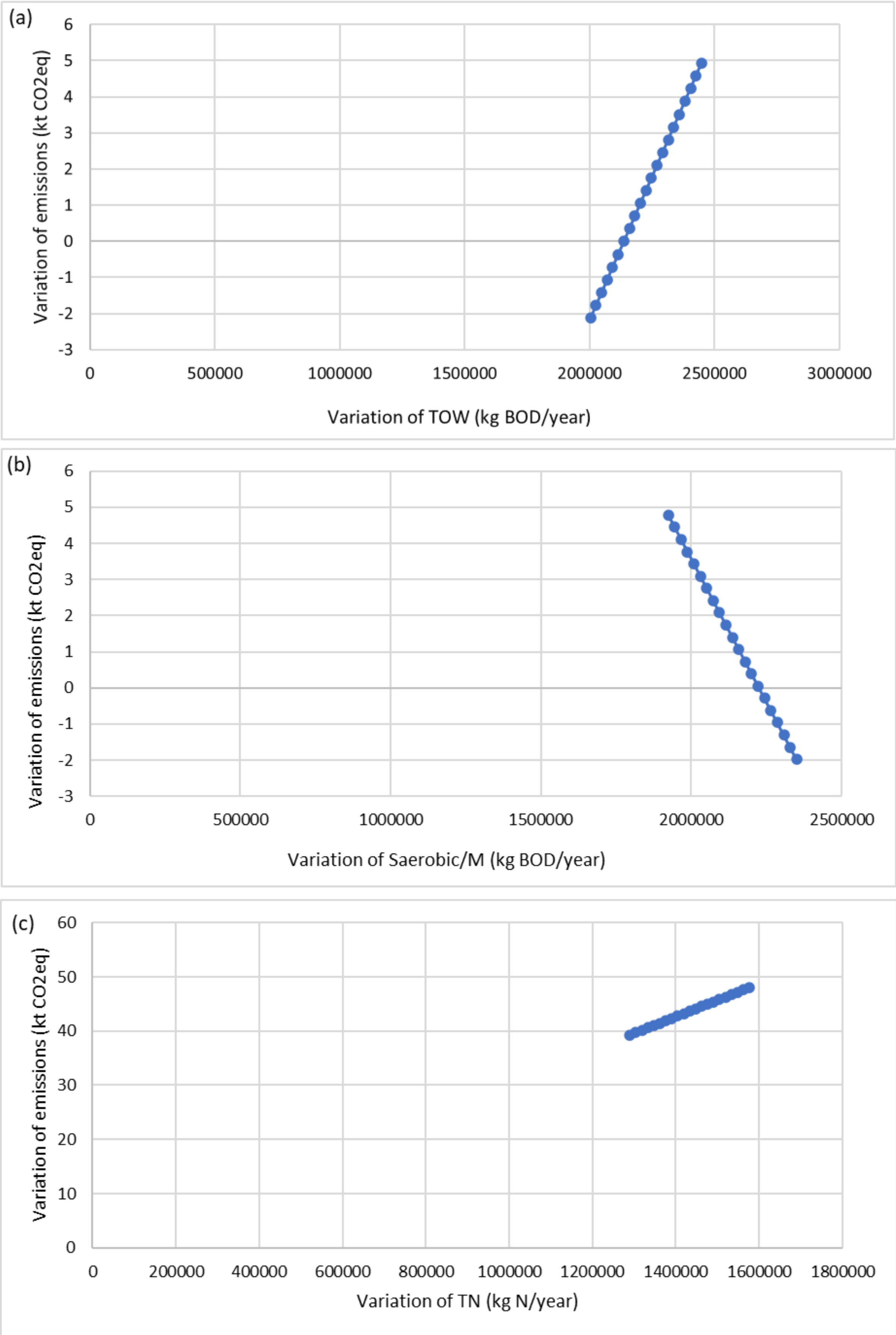

Figure 4- 6: Variation of emissions with variation of input parameters

emissions interval (Figure 4-6 (b)). Therefore, emissions from activated sludge process increase with the quantity of treated wastewater and its organic content and decrease with the increase of process efficiency of the organic content removal from wastewater.

N_2O emissions are influenced by TN and could reach a maximum of 48.01 kt CO_{2eq} when TN= 1,576,650 kg N/year (Figure 4-6 (c)). Thus, the intensity of nitrification and denitrification processes are determinant for N_2O 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.

4.5. Conclusion

This topic 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 (126.59 kt CO_{2eq}).

In total, N_2O emissions were the highest type of emissions, followed by CO_2, and the minor emissions were methane emissions. N_2O emissions from activated sludge were the most important source of emissions (43.65 kt CO_{2eq}), followed by CO_2 emissions from external electricity consumption (38.57 kt CO_{2eq}), CO_2 emissions from cogeneration (36.16 kt CO_{2eq}), discharged water after treatment (5.30 kt CO_{2eq}), anaerobic digestion (1.50 kt CO_{2eq}) and finally, CH_4 from activated sludge (1.40 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 topic 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.

5. Assessment of the Environmental Impacts of Wastewater Treatment in Tunisia

5.1. Introduction

Wastewater treatment and energy recovery from biogas have gained much interest over the years as an effective strategy to waste management [33], [163]. Biogas can be produced from different sources, including sludge produced in WWTPs [164], [165]. It is, however, important to continually evaluate the impact of both wastewater treatment and biogas production on the environment, especially with the current worldwide concern about reducing GHG emissions and their effect on human life [166]. The unceasing improvement of the employment of wastewater treatment and biogas limiting their GHG emissions will encourage increasing their use on broader scales [167].

In the same context, sludge disposal in landfills and the slow introduction of electricity production from biogas in WWTPs in Tunisia represent some evidence indicating that the performance of WWTPs is still flawed [43], [44]. The accomplishment regarding the wastewater treatment rate in Tunisia contradicts the slow advancements made in the sector regarding the management of its various impacts and the implementation of new technologies. It also does not comply with the policies related to GHG emissions mitigation and goals governing the wastewater treatment sector that first aim to limit the harm from human-generated wastes [45]. It should be mentioned nonetheless that there are some solutions under study and efforts to solve wastewater-related problems, like integrated energy production from biogas, but these solutions are slowly applied to all the WWTPs in the country [48]. A previous study was done in the case of Tunisia that predicted emissions quantities (CH_4, CO_2, and N_2O) from wastewater treatment in the case of countrywide biogas production from some processes. However, this study did not reflect the impact of these emissions on the environment, and the estimations were limited to only certain emissions types [168].

Hence, Tunisia represents an appealing study target for the problem of the impact of biogas production from the wastewater treatment sector on the environment to understand its possible future improvement horizons and to enlighten decision-making stakeholders on the problems that should be considered to achieve sustainability in the field.

One of the tools to evaluate the effects of a process or a product on the environment is LCA. LCA allows analyzing and interpreting GHG emissions data's effect on different environmental impact categories. Environmental practitioners have widely used it for its practicality and effectiveness in solving environmental issues and decision-making [169]. An effective LCA should comply with the ISO 14040 requirements. It should then include a clear definition of the goal and scope or boundaries of the study with detailed assumptions made, a well-explained life cycle inventory, a life cycle impact assessment (LCIA), and finally, an interpretation of the results [91], [170], [171]. LCIA follows four steps. The first step is characterization, where the contribution from each element or process to impact categories is calculated by multiplying the amount of each element by a corresponding characterization factor. The second step is damage assessment, in which the same unit's impact categories are summed up into damage categories. After that is the normalization of the results, which means the conversion of all the impact category indicators into the same unit. The last step is weighting, where the results are multiplied by weighting factors and added to make a total or single score, an indicator used to rank a product or substance by the environmental impact it creates and expressed in the unit point (Pt and kPt). Increasing single score points indicate a higher environmental impact and vice versa [172].

Several previous studies used LCA for the environmental assessment of WWTPs with or without biogas production [29], [92], [103], [173]. Most of these LCA studies regarding this topic were focused on specific areas like Europe, and more specifically, many of them were about Germany [29], [104], [106]. For example, Hijazi et al. (2016) reviewed 15 LCA studies in Europe, and five were in Germany [28].

On the other hand, few LCA studies can be found about developing countries. This can be explained by the lack of focus on the environmental impact of the wastewater sector, making it an unresolved sustainability challenge in these regions, whether because of the low connection rate to WWTPs or the lack of necessary data for the studies [174]–[176]. The geographical distribution of LCA studies in developing countries is also limited; most are about India and China [174]. For instance, the Middle East and North Africa (MENA) did not have many LCA studies in the literature though they share many environment-related problems. Three papers on Iraq and one on Iran have conducted LCA of WWTPs even if waste management and its related issues, such as exposure to emissions and declining air quality, is one of these most highlighted problems [115], [177]–[179]. According to World Bank statistics, the MENA region registered four times faster growth than the world's average CO_2 emissions. Additionally, the climate change forecast shows that the risk for increasing harm is higher for this region than for the rest of the world [180]. The lack of application of strategies and policies concerning emissions is one of the reasons for the slow progress of waste management, and this is caused by the lack of contributing efforts to provide the necessary information in this regard [115]. Thus, evaluating the impacts of emitting sectors, such as wastewater treatment, can help clarify and map shared struggles and root causes (climate, social, and political situation) in the MENA region to look for sustainable ways to address those.

Therefore, this study aims to assess the environmental impacts of wastewater treatment in Tunisia by conducting an LCA of the WWTPs in the country. The human health and environmental impacts from the resulting GHG emissions will be evaluated to clarify the sustainability performance of substitutional possible scenarios.

The following section presents an introduction to the current wastewater management in Tunisia. It is followed by describing the study's methodological approach in conducting the LCA and presenting the results and discussions. The last section incorporates the critical implications and the study conclusions.

5.2. Materials and Methods

5.2.1. Description of the study area

It is understood that large-scale WWTPs are subject to higher emissions and, consequently, a more substantial environmental impact. Currently, the number of WWTPs that have already built anaerobic digestion and cogeneration units is limited. Therefore, for this study, a large-scale WWTP with installed biogas production and use unit was selected as a case study. Such a large-scale WWTP can better represent a model for wastewater treatment in Tunisia from which the present environmental profile can be analyzed.

This LCA was conducted for a WWTP equipped with a biogas production unit in Tunisia. It also has been selected as the case study since the plant-specific data were already accessed, and consequently, the results can be more accurate. The studied WWTP is in the southwest of Tunisia in the region of Gafsa. It serves 184,000 populations and treats, on average, 10,386 m^3 (min 7,047 m^3- max 15,565 m^3) daily of a mix of domestic and industrial wastewater. The WWTP also has two installed anaerobic digesters with a volume of 2,746 $m^{3,}$ each capable of producing 3,350 m^3 of biogas daily, and two cogenerators producing 330 kW each [129]. Input and output wastewater characteristics are shown in Table S2 in the supplementary material.

5.2.2. Study boundaries and scenarios description

The functional unit is one person connected to the wastewater treatment network. This functional unit was set because the objective of this research is to assess the impact of one WWTP, and the treatment capacity in terms of the number of connected populations and quantity of wastewater generated was considered the main influencing factor; therefore, the functional unit is population equivalent which expresses the amount of pollution produced by one person.

The system boundary in this study was the life cycle of one WWTP from the cradle to the grave. Hence, we included the construction and demolition of the plant and wastewater treatment process by activated sludge in all the scenarios. Biogas production has not yet launched in Gafsa WWTP, and all the sludge is sent to landfills. Therefore, the baseline scenario, which will reflect the impact under the current working conditions, consists of the following processes: WWTP construction, electricity consumption (from the grid), wastewater treatment, sludge landfill, and WWTP demolition.

The alternative processes were selected based on realistic options that can be explicitly applied to the case of Tunisia without huge investments, considering the availability of its resources. For example, biogas production by anaerobic digestion is already an option used traditionally on small scales by farmers to treat animal manure in Tunisia and is recently under feasibility study for installation in WWTPs [44]. Biogas can be used to produce heat and part of the electricity needed by the plant by cogeneration. Sludge drying is also better than landfilling since it can be used as agricultural fertilizer [181]. This practice has been used in Tunisia but was limited to small quantities, and few WWTPs and current studies are being conducted to extend its use by all the WWTPs in Tunisia [43].

Additionally, It was reported that the quantity of produced municipal solid waste is approximately 2.60 million tons/ year, of which 63.20% is a wet organic matter [182]. Solid waste disposal is a severe problem in Tunisia. It is usually burned or landfilled in uncontrolled landfills, causing severe environmental damage [151]. Therefore, we considered the option to transport a small part of the municipal solid waste to be mixed with sludge for anaerobic digestion instead of sending it to landfills.

Hence, the suggested scenarios include the previously mentioned options already under feasibility study by the government to improve the wastewater treatment sector in Tunisia.

Scenario 1 is the same as the baseline scenario but with biogas production by anaerobic digestion process, partial electricity production by cogeneration and sludge drying instead of sludge landfilling.

Scenario 2 is similar to scenario 1 but considers the anaerobic digestion of WWTP's sludge mixed with solid waste transported to the plant.

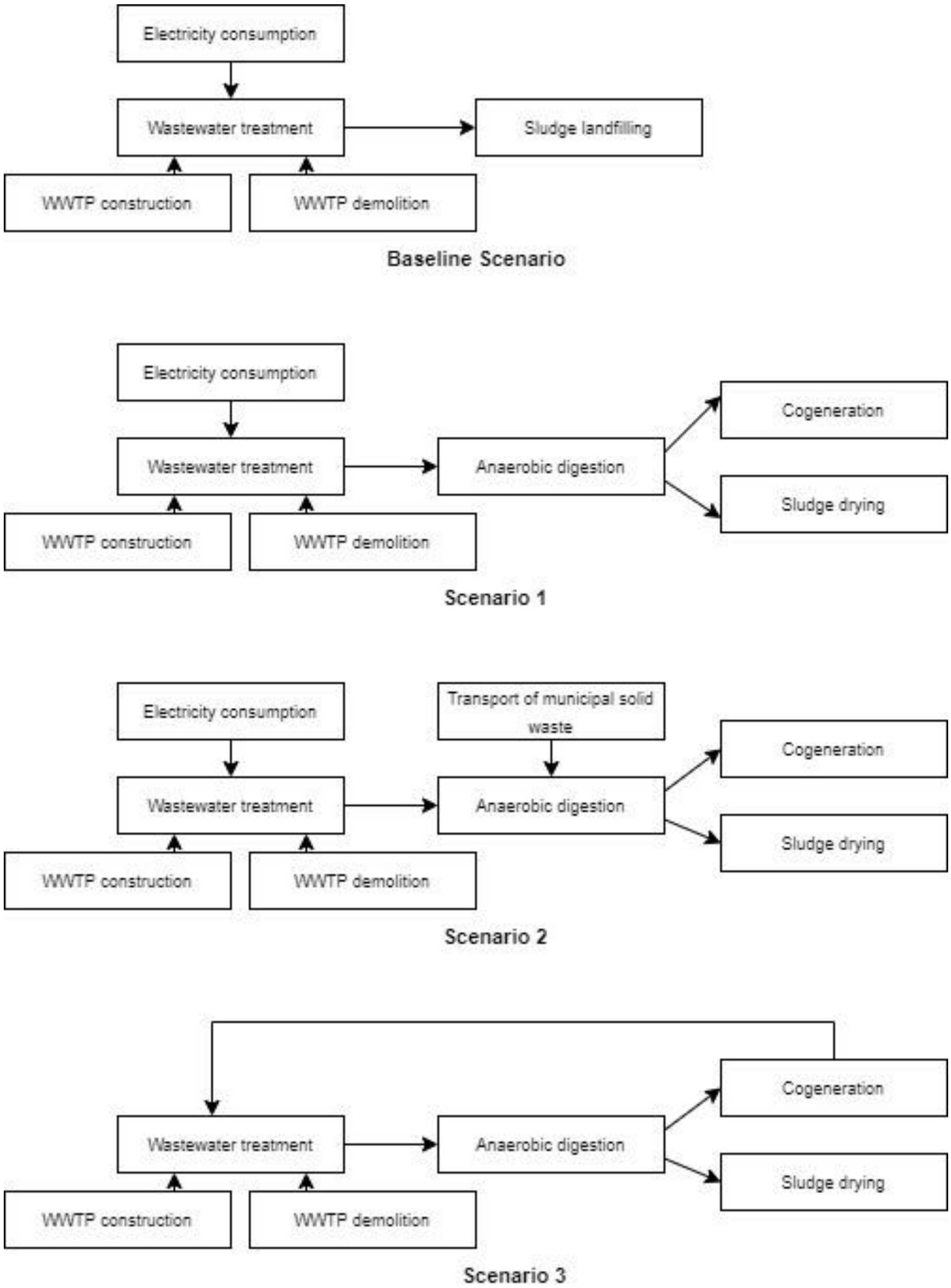

Figure 5- 1: Scenarios description

In Scenario 3, the cogeneration engine supplies all the plant's electricity consumption. This scenario was suggested because any electricity produced from a renewable energy source in Tunisia should be injected into the national electricity grid [183]. Using its own produced electricity will make the plant self-sufficient and help avoid additional costs of connecting to the grid and all the equipment needed. Hence, scenario 3 is like scenario 1, but all the electricity consumed by the plant is produced by cogeneration, and consequently, no electricity is taken from the grid. Figure 5-1 illustrates the processes involved in each scenario.

5.2.3. Life cycle inventory

SimaPro 9.1.1.1, one of the leading cost-effective and science-based tools, was used to conduct the LCA because it features high datasets treatment capacity and large specific databases [184] [185]. For the life cycle inventory of this research, Ecoinvent 3 database integrated into the software was selected as it includes large datasets and is continuously updated [186], [187]. All the background data for processes including inputs (energy and material) and outputs (products, wastes and emissions) were selected from Ecoinvent 3 database and correspond to processes for the rest of the world (RoW) since country specific processes of Tunisia are not covered by the database. Since this research focus on impact of GHG emissions on the environment essentially, emissions inventory for each process are presented from Table 5-1 to Table 5-8.

Table 5- 1: Emissions inventory of 1 MJ Electricity consumption process

Substance	Unit	Value
Carbon dioxide, biogenic	g	5.01
Carbon dioxide, fossil	g	288.23
Carbon monoxide, biogenic	mg	5.41
Carbon monoxide, fossil	mg	43.98
Methane, biogenic	µg	283.64
Methane, fossil	mg	122.14
Nitrogen oxides	mg	169.85

After selecting the processes, the scenarios were created on SimaPro. Each scenario comprises the processes included and the corresponding unit processes inputs to the scenario description.

Table 5- 2: Emissions inventory of Wastewater treatment process in 1 wastewater treatment plant

Substance	Unit	Value
Carbon dioxide, biogenic	t	-26.14
Carbon dioxide, fossil	kt	5.29
Carbon monoxide, biogenic	kg	326.54
Carbon monoxide, fossil	t	36.33
Methane, biogenic	kg	92.99
Methane, fossil	t	13.29
Nitrogen oxides	t	15.03

Table 5- 3: Emissions inventory of 1 m3 Biogas (Anaerobic digestion process)

Substance	Unit	Value
Carbon dioxide, biogenic	g	17.08
Carbon dioxide, fossil	g	353.71
Carbon monoxide, biogenic	mg	18.74
Carbon monoxide, fossil	mg	361.54
Methane, biogenic	g	87.21
Methane, fossil	mg	940.28
Nitrogen oxides	mg	527.83

Table 5- 4: Emissions inventory of 1 kg Sludge landfill

Substance	Unit	Value
Carbon dioxide, biogenic	g	84.25
Carbon dioxide, fossil	g	8.27
Carbon monoxide, biogenic	µg	42.59
Carbon monoxide, fossil	mg	17.23
Methane, biogenic	g	38.91
Methane, fossil	g	1.78
Nitrogen oxides	mg	53.67

The impact assessment is for one year long of operation of the WWTP. Gafsa WWTP provided the yearly operational data: electricity consumption, biogas production capacity (anaerobic digestion) [43]. The amount of sludge produced, electricity by cogeneration were assumed by authors based on operational conditions of the plant.

Construction and demolition of the plant and wastewater treatment processes data on Ecoinvent 3 are for one plant and classified by size based on the treatment capacity which was also provided by Gafsa WWTP.

Table 5- 5: Emissions inventory of 1 kg Sludge drying

Substance	Unit	Value
Carbon dioxide, biogenic	mg	163.47
Carbon dioxide, fossil	g	9.09
Carbon monoxide, biogenic	µg	350.15
Carbon monoxide, fossil	mg	21.26
Methane, biogenic	µg	54.33
Methane, fossil	mg	7.34
Nitrogen oxides	mg	41.62

Table 5- 6: Emissions inventory of 1 MJ Cogeneration

Substance	Unit	Value
Carbon dioxide, biogenic	kg	1.29
Carbon dioxide, fossil	g	-125.01
Carbon monoxide, biogenic	mg	-752.90
Carbon monoxide, fossil	mg	343.43
Methane, biogenic	g	4.71
Methane, fossil	mg	226.02
Nitrogen oxides	mg	805.95

Table 5- 7: Emissions inventory of 1 tkm Transport of solid waste

Substance	Unit	Value
Carbon dioxide, biogenic	g	15.09
Carbon dioxide, fossil	g	526.90
Carbon monoxide, biogenic	mg	29.93
Carbon monoxide, fossil	g	1.29
Methane, biogenic	mg	3.41
Methane, fossil	mg	476.37
Nitrogen oxides	g	2.03

Table 5- 8: Emissions inventory of the construction of 1 wastewater treatment plant

Substance	Unit	Value
Carbon dioxide, biogenic	t	12.75
Carbon dioxide, fossil	t	841.88
Carbon monoxide, biogenic	kg	86.72
Carbon monoxide, fossil	t	6.31
Methane, biogenic	kg	23.71
Methane, fossil	t	1.97
Nitrogen oxides	t	2.44

Regarding the quantity of municipal solid waste transported to the WWTP, we assumed that this option is a first test trial, and therefore it was assumed that 100 tons of waste would be transported in the first year within a maximum distance of 50 km, so the unit used was tonne-kilometre (tkm). This quantity of solid waste represents only 3.66 % of the annual treated wastewater, and therefore won't change the annual wastewater treatment capacity and its related emissions. Consequently, only the transportation process and its impact were considered as representative of this option.

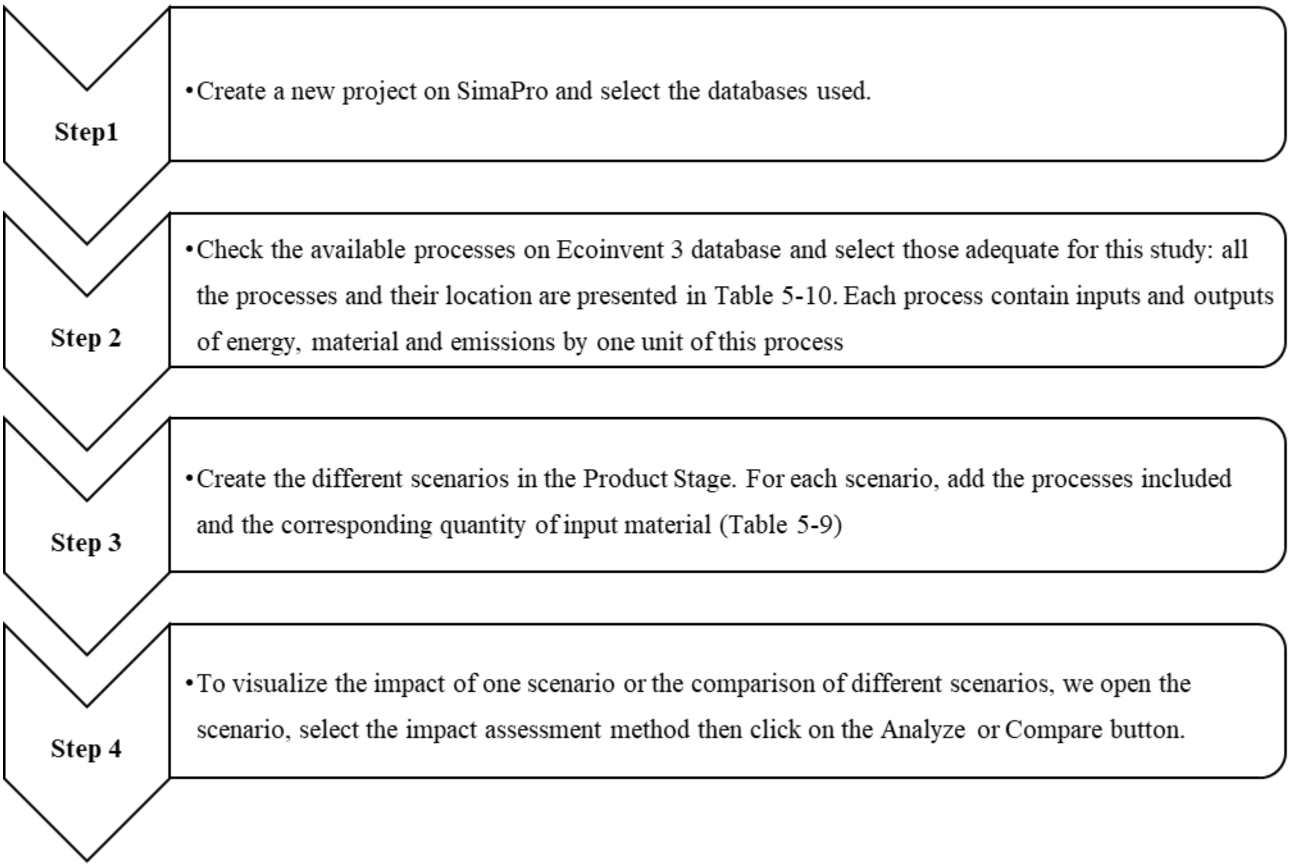

Figure 5- 2: Steps of building an LCA on SimaPro

The yearly input data for each unit process are presented in Table 5-9. The steps of performing the LCA are presented in Figure 5-2.

Table 5- 9: Input data for each scenario

Process	Baseline scenario	Scenario 1	Scenario 2	Scenario 3
Construction of the plant	1 plant			
Electricity consumption	1,924,286 kWh			
Wastewater treatment	1 plant			
Sludge landfill	5000 tons			
Anaerobic digestion		1222750 m^3		
Cogeneration		10000 kWh		1924286 kWh
Sludge drying		5000 tons		
Demolition of the plant	1 plant			
Transportation of solid waste			5000 tkm	

Table 5- 10: Processes used from the Ecoinvent 3 database and their location

Process	Process name in the library	Category
Electricity consumption	Electricity, high voltage {TN} market for electricity, high voltage- Ecoinvent 3- consequential- system	Energy/ Electricity country mix
Wastewater treatment	Wastewater treatment facility, capacity 1E9l/year {GLO}market for- Ecoinvent 3- consequential- system	Processing/ Waste
Sludge landfill	Municipal solid waste {GLO} treatment of municipal solid waste, unsanitary landfill, moist infiltration class (300 mm)- Ecoinvent 3- consequential- system	Waste treatment/ Landfill
Anaerobic digestion	Biogas {RoW} treatment of sewage sludge by anaerobic digestion- Ecoinvent 3	Material/ Fuel/ Biofuels/ Biogas
Cogeneration	Electricity, high voltage {RoW} heat and power co-generation, biogas, gas engine- Ecoinvent 3- consequential- system	Energy/ Cogeneration/ Biomass
Sludge drying	Sewage sludge, dried {RoW} market for sewage sludge, dried- Ecoinvent 3- consequential- system	Waste treatment/ Biowaste
Transportation of solid waste	Transport, freight, lorry {RoW} market for transport- Ecoinvent- consequential- system	Transport/ Road
Construction of the plant	Assembly of: Concrete block {RoW} and clay brick {RoW}- Ecoinvent 3- consequential- system	Material/ Construction
Demolition of the plant	Waste scenario of: Waste concrete {RoW} and waste brick {RoW}- Ecoinvent 3- consequential- system	Waste treatment/ Construction waste

5.2.4. Life cycle impact assessment (LCIA)

The LCIA was made for 100 years and, as a result, ReCiPe 2016 Midpoint (H) and Endpoint (H). ReCiPe Midpoint method enables an understanding of the environmental intervention's effect or score on specific impact categories and is calculated as follows [188]:

$$IS = \sum x \sum i \ (CFx, i * mx, i) \tag{5-1}$$

Where: IS = impact score, CF = characterization factor, m = life cycle intervention, x = substance, i = emission compartment. In this research, the default characterization factors on SimaPro were used, and the characterization calculation is presented in Table B2 [184].

At the same time, ReCiPe Endpoint is a damage-oriented method that shows the final impact on damage categories from an environmental intervention [189]. ReCiPe Endpoint method groups impact into three damage categories: human health, represented by Disability Adjusted

Life Years (DALY), ecosystems represented by years in which specific species in a particular area are lost; and resources, represented by extra costs of future resource production over time [190]. The relationships between ReCiPe Midpoint impact categories and ReCiPe Endpoint damage categories of this research are shown in Fig. B1 in the supplementary material.

LCIA follows four steps: characterization, damage assessment, normalization, and weighting. The results are presented in single scores, an indicator used to rank a product or substance by the environmental impact it creates; it is expressed in the unit point (Pt) and calculated as follows:

$$SS = \sum_{i} D_i \times w_{D_i} \tag{5-2}$$

Where: Di = damage indicator for damage category i, and w_{Di} = weighting factor of damage indicator i.

Increasing single score points indicate a higher environmental impact and vice versa [172].

5.3. Results and Discussion

5.3.1. Analysis of the baseline scenario

The results of the contribution to the total environmental impact and the contribution to the impact assessment characterization from the different processes of the baseline scenario are shown in Table 5-11 and Figure 5-3. The highest contribution to the total environmental impact of the WWTP is 42.30% from the wastewater treatment process, followed by 41.40% from sludge landfilling. Electricity consumption, construction of the plant, and demolition contributed respectively with 10.10%, 5.78%, and 0.37%.

Table 5- 11: Contribution of each process to the total environmental impact of the WWTP

Process	Contribution to the total environmental impact (%)
Construction of the plant	5.78
Electricity consumption	10.10
Sludge landfill	41.40
Wastewater treatment	42.30
Demolition of the plant	0.37

The single score impact assessment expressed in kilo points (kPt) of the baseline scenario is presented in Figure 5-4. The processes with the highest score in kPt indicate the most damaging processes to the environment. Results show that the WWTP's impact on human health damage category is 329 kPt from wastewater treatment, 330 kPt from sludge landfill, 79 kPt from electricity consumption, 45 kPt from the construction of the plant and 4 kPt from plant demolition.

Sludge landfill and wastewater treatment are the main contributors to human health damage. The high emissions of CO_2 from wastewater treatment and electricity consumption and CH_4 from sludge landfill severely affect global warming, contributing to the increase in malnutrition and various diseases [191], [192]. In addition, the effect of wastewater treatment was also crucial in ozone formation, stratospheric ozone depletion, and particulate matter categories causing an increase in respiratory diseases. Electricity consumption highly affects ionizing radiation, which is responsible for increasing cancer risk; however, for the same impact category, there is an environmental benefit from plant construction [193]. Actually, construction materials (sand, brick, or concrete) have a shallow radiation effect and can block radiation and consequently result in an environmental benefit in the long term [194].

The scores from damage to ecosystems were 17 kPt from wastewater treatment and 12 kPt from sludge landfill, and 4 kPt from electricity consumption and construction of the plant. The effect of wastewater treatment on the ecosystem damage category is explained by its high effect on land use, terrestrial acidification, and terrestrial ecotoxicity, causing all direct damage to terrestrial species. The use of chemicals during the treatment process and the discharge of the effluent in surrounding areas may be the reason for these effects [195]. However, sludge landfill affects marine ecotoxicity leading to damage to marine species. Nitrogen-derived emissions are responsible for these effects.

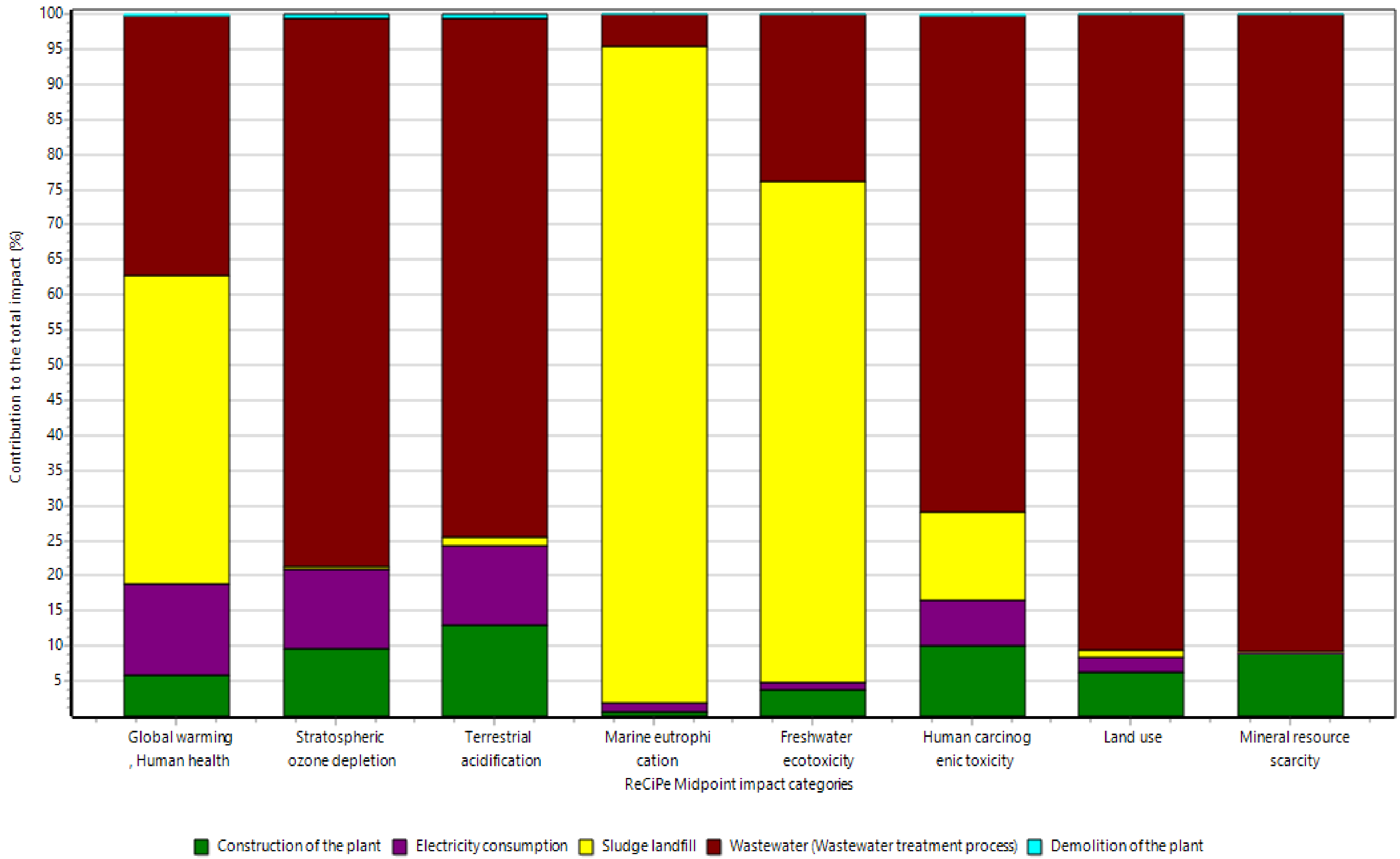

Figure 5- 3: ReCiPe Midpoint characterization results for baseline scenario

The impact on the resources damage category is negligible except for wastewater treatment caused mainly by land use and water consumption inside the WWTP.

A similar previous study by Blanco et al. (2016) also showed that the impact of WWTP on the human health category is more critical than on ecosystems and resources [29].

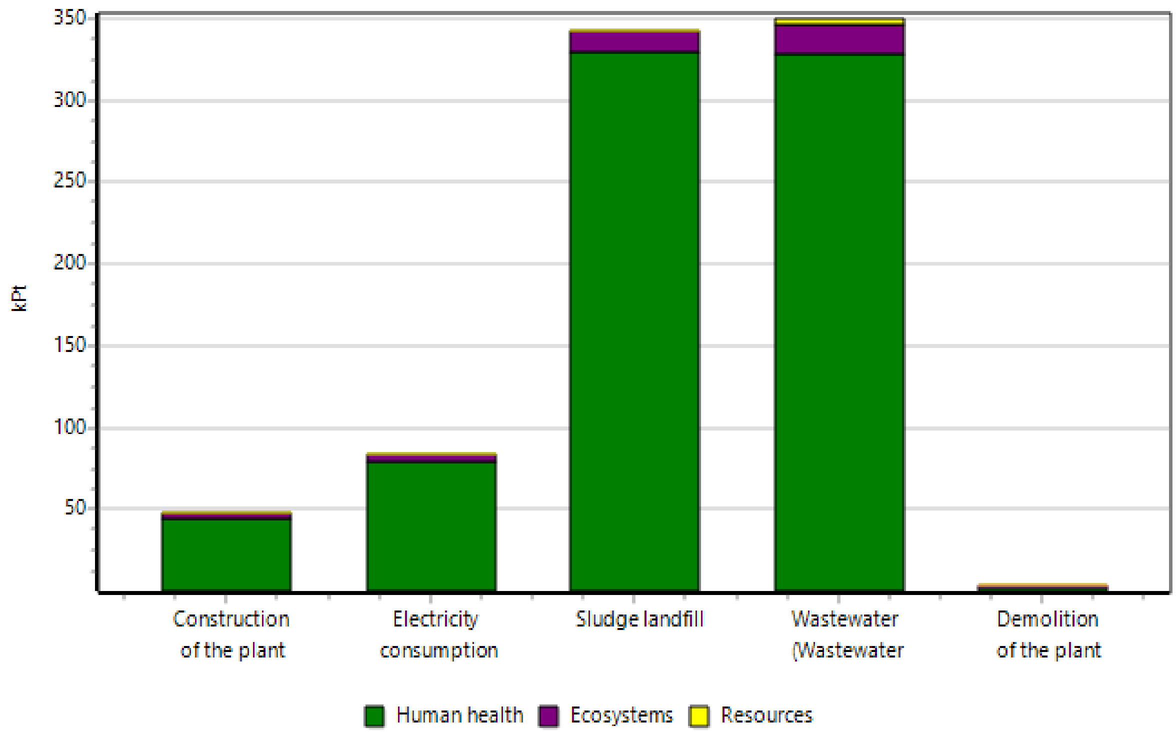

Figure 5- 4: Damage assessment of the baseline scenario (single score)

The impact of the plant construction is mainly caused by the electricity used in the construction works, while the plant's demolition does not have a significant environmental impact. Hijazi et al. (2016) suggest that an extended plant lifetime would even reduce the impact of construction and demolition more [28].

In another LCA study by Alanbari et al. (2015) of Al-Hilla WWTP located in Iraq, another MENA country with a capacity comparable to this research (12,000 m^3). The LCA results were 40 Points/m^3 compared to 59 Points/ m^3 in this LCA confirming that the results of this research are within the range of impact scores in the same region and under similar conditions. Human health damage category was the most affected by a score of 30 Points/ m^3 versus 57 Points/ m^3 from the same category in this research. The impact on resources damage category from Al-Hilla WWTP and Gafsa WWTP were respectively 8 Points/ m^3 and < 1 Point/ m^3 which can be explained by the complexity of the secondary and tertiary treatment in Al-Hilla WWTP requiring more expenses on chemicals and electricity. The impact on ecosystems quality was 2 Points/ m^3 for both Al-Hilla and Gafsa WWTP and [179]. The other LCA study did not however consider the impact from sludge disposal which is the second highest impact process in the present research and that can explain the difference in results.

The results confirmed a considerable effect of the wastewater treatment current scenario in Tunisia. The main impact is pictured on human health (95% of the total environmental damage), which contradicts one of the ONAS goals to ensure better life quality for citizens by providing sanitation services [48]. GHG emissions during wastewater treatment, especially activated sludge, are the main reason for this negative impact. This can be explained by the fact that ONAS prioritizes the connection of the maximum of municipalities, especially those in interior regions while planning its budget [43]. Improving the wastewater treatment process by using the latest technologies that are at the same time efficient and eco-friendly is also one of its goals. However, this goal is not as prioritized yet as the extension of the ONAS network [49]. The effect of sludge landfill is also significant since landfilling is the easiest and cheapest option. The harmful effects of landfilling are especially pictured in the capital Tunis in the province of “Borj Chakir” and around the marsh “Sijoumi”, which are the two largest landfills in Tunisia that were the subject of conflict for the different stakeholders for all the health problems that raised in people living in the surrounding area. Heavy metals' contamination of the soils makes them unsuitable for agriculture [196]. This problem is becoming more urgent to solve because of the health diseases it is causing, especially for close areas directly exposed to hazardous substances from the disposal.

5.3.2. Comparison of the alternative scenarios

The second goal of the LCA is to compare the baseline scenario to alternative scenarios considering biogas production. The impact assessment single score results are shown in Figure 5-5. Figure 5-6 shows the details of the single score in kPt from each process in the different scenarios to explain their contribution to making the differences between scenario results in Figure 5-5.

The baseline scenario scored 786 kPt on human health, while scenario 1 and scenario 2 contributed 547 kPt each and 585 kPt from scenario 3 to the same damage category.

As explained before, the impact on ecosystems is almost the same as the different scenarios and is caused by the wastewater treatment process, which is the same in all the scenarios.

The impact on the resources damage category is also similar (~ 4.6 kPt) but slightly higher for scenario 3 (5.4 kPt). Initial costs and additional costs for maintenance of the cogeneration engines also indirectly affect resource availability in terms of investment cost. Additionally, this difference can be explained by the need for supplementary natural gas for the cogeneration engines functioning since biogas has a low calorific value, and the quantity produced cannot be enough for extended working hours to cover all the plants' needs in electricity [197].

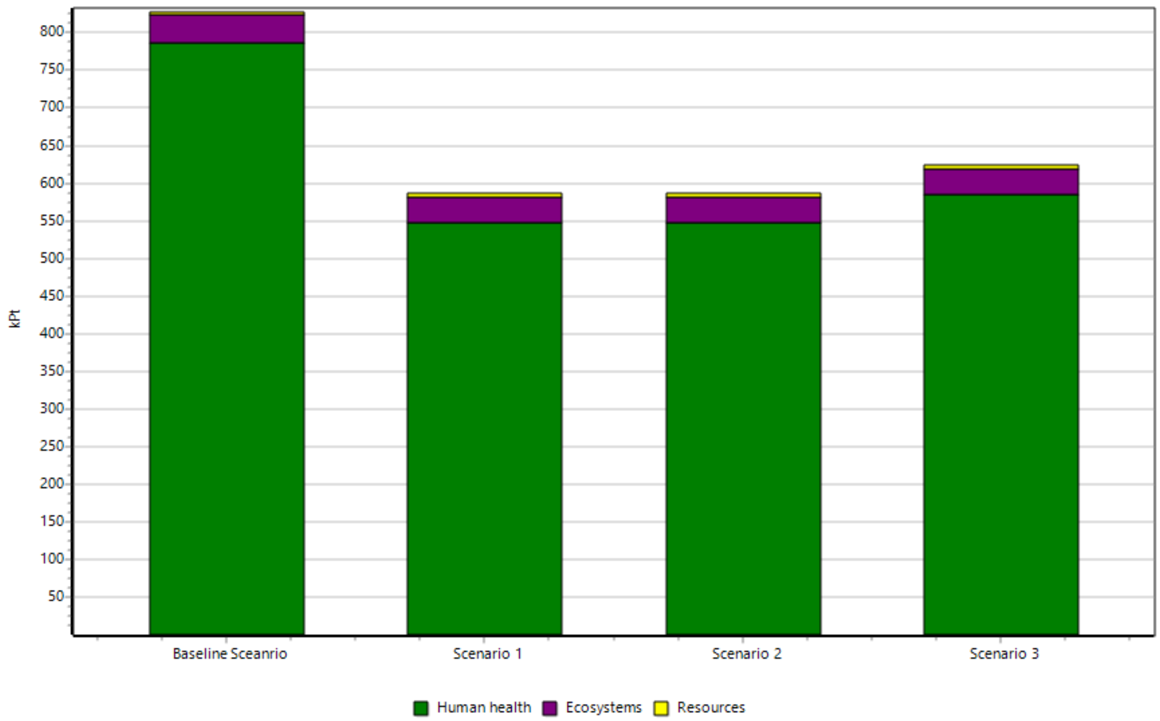

Figure 5- 5: Comparison of the damage from the different scenarios (single score)

Since wastewater treatment and sludge landfilling had the most impact on human health in the baseline scenario (respectively 41.80% and 41.90%), introducing biogas production and replacing sludge landfilling with sludge drying considerably reduced this impact in the other scenarios (by 30.41% for scenario 1 & 2 and by 25.57% for scenario 3), rendering baseline scenario the worst when it comes to human health.

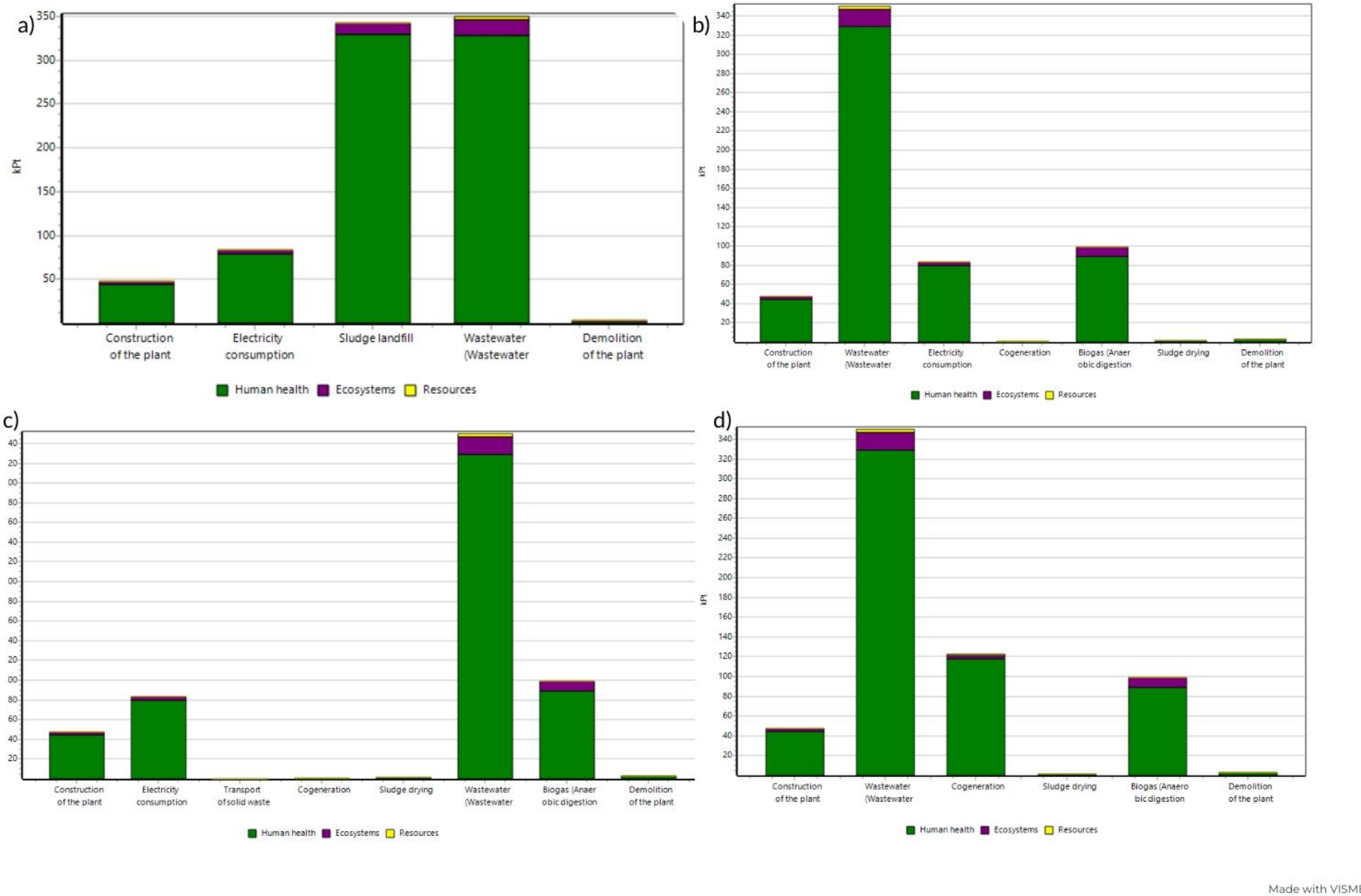

Figure 5- 6: Impact assessment of different scenarios in single scores: (a) baseline scenario, (b) scenario 1, (c) scenario 2, (d) scenario 3[198]

Overall, results highlighted that the wastewater treatment process under its present operative mode is a source of significant damage to human health. Aerobic treatment of wastewater especially activated sludge process and chemicals used are the major emissions spots. This suggests that further efforts from the government should be carried out regarding this problem. There are currently several wastewater treatment technologies that guarantee better-advanced treatment and efficiency with lesser emissions in the market that can replace activated sludge process. For instance, an aerobic membrane bioreactor (MBR), sequencing batch reactor (SBR), and an up-flow anaerobic sludge blanket (UASB) are technologies that have better performance and less impact on the environment than activated sludge [199], [200]. Since the hot temperature season is recently longer than years ago in Tunisia (it could exceed 40 degrees Celsius in August) because of climate change, UASB can be a beneficial investment in the case of Tunisia [201], [202]. This technology combines anaerobic wastewater treatment and digestion and is used by many countries especially those with long hot weather periods. Previous studies confirmed that it requires lower energy consumption and generates less sludge [203]. It has also been proven that UASB technology reduces CH_4 and hydrogen sulfide (H_2S) emissions from the wastewater treatment process [82], [204]. Therefore, using UASB can reduce initial investment cost for anaerobic digestion, improve the wastewater treatment line, saving energy costs and reduce the environmental impact of emissions from all related processes.

In Tunisia, it is also necessary to stop sludge landfilling and accelerate the shift towards sludge drying as it is a low-cost option. According to a study by the Institute of Heat Engineering and Air Protection, Krakow University of Technology, Poland, it costs 14 euros to 1 m^3 of sludge with 25% dry solids [205]. Some WWTPs already use natural and mechanical sludge drying in Tunisia, but the most limiting problem is the need for extended areas to be used as beds to dry the sludge in the case of biological sludge drying [43].

Scenario 1 and scenario 2 have almost the same impact profile, which leads to conclude that the transport of solid waste to the WWTP for anaerobic digestion with sludge does not significantly affect the environment. However, scenario 2 represents a good option for solid waste management by reducing the solid waste quantities disposed of in landfills and their impact on the environment. Mixing wastewater sludge with solid waste will also improve the efficiency of anaerobic digestion and increase the methane yield in the produced biogas because of the high organic content in solid waste [206], [207].

Scenario 3 has a higher impact on the human health damage category than scenarios 1 and 2. When the electricity produced by cogeneration was required to cover the plants' regular electricity consumption, this process's impact became considerable. This impact may be caused by the amount of CO_2 in the exhaust of the engines and their effect on global warming. Consequently, extended cogeneration use can cause more damage than buying electricity from the national grid. However, these results indicate that produced biogas can be utilized in other ways, like its injection into the national gas network and its use for cooking, heating, and other purposes [77].

Therefore, scenario 2, in which solid waste is mixed with sludge and part of the electricity is produced by cogeneration, and the other part is supplied from the grid, would be the best performance scenario with reduced impact on the environment in the case of Tunisia.

5.3.3. Comparison of different WWTPs in Tunisia

In order to understand emissions profiles and potential issues from the wastewater treatment field and analyze and suggest solutions to improve it, it is better to follow the functioning of multiple plants instead of only one plant and identify patterns in their working mode. Therefore, in this part, 3 WWTPs were selected based on different criteria: 1) All are large scale WWTPs hence connected to a sizable number of populations, 2) All are equipped with biogas production unit and are intended to start producing biogas in the future, 3) The plants are selected in different regions: capital, north coast and interior.

- Choutrana II WWTP:

Choutrana II WWTP is in the capital area and belongs to Ariana governorate. It started in 2007. This WWTP is connected to a population of 333,000 (2012). The main treatment type is prolonged aeration (low load). Wastewater treatment is carried out in three stages: pre-treatment, secondary treatment, and tertiary treatment. It produces a daily sludge amount between 2,189 and 2,420 m^3/day and dry sludge amount between 1,915 and 2,420 m^3/day. The sludge treatment chain includes thickening and dewatering with two thickeners of 1,250 m^3, each [208]. The data of the treated wastewater characteristics is represented in the Table 5-12.

Table 5- 12: Wastewater treatment data (Choutrana WWTP)

Daily treated wastewater	42,228 m^3 (2000 m^3/ hour)
BOD_5	17,339 kg/ day
COD	42,306 kg/ day
TSS	18,162 kg/ day

- Nabeul SE4 WWTP:

Nabeul SE4 WWTP is located in the Northeast of Tunisia in the Nabeul governorate. It was constructed in 1979 and renewed in 2016 to increase its capacity from 9,585 m^3/day to 24,500

m^3/day. It is connected to 172,800 people. The process in this WWTP consists of degreasing, grain removal, primary settling, nitrification-denitrification with phosphorus removal and biological treatment with activated sludge. The sludge line consists of mechanical sludge dewatering, anaerobic stabilization by digestion and cogeneration by biogas recovery. The treatment of odors is carried out by photoionization. The tertiary treatment of the purified water will be carried out by continuous filtration and treatment by UV radiation [209], [210]. The data of the treated wastewater is presented in the Table 5-13.

Table 5- 13: Wastewater treatment data (Nabeul SE4)

Capacity/ design flowrate	24,500 m^3/ day
Actual daily treated wastewater	16,538 m^3
BOD_5	7,773 kg/ day

- Life cycle assessment:

The life cycle assessment of scenario 1 was performed for the 3 WWTPs to compare their impact. The input data were chosen based on assumptions made by the authors (like Gafsa WWTP) and presented in the Table 5-14.

Table 5- 14: Life cycle assessment input data

Process	**Gafsa WWTP**	**Choutrana II WWTP**	**Nabeul SE4 WWTP**
Construction of the plant	1 plant	1 plant	1 plant
Electricity consumption	1,924,286 kWh	2,500,000 kWh	2,000,000 kWh
Wastewater treatment	1 plant	1 plant	1 plant
Sludge drying	5,000 tons	15,000 tons	5,000 tons
Anaerobic digestion	1,222,750 m^3	2,500,000 m^3	1,500,000 m^3
Cogeneration	10,000 kWh	25,000 kWh	10,000 kWh
Demolition of the plant	1 plant	1 plant	1 plant

Figure 5-7 represents single score results of the comparison of impact of the 3 WWTPs.

Choutrana II has the highest impact on human health damage category followed by Nabeul SE4 then Gafsa WWTPs. It can be understood that the increase in quantity of treated wastewater increases the total impact of the plant especially on human health category. However, the impact on ecosystems and resources damage categories was not noticeable. Choutrana II WWTP is located in a densely populated and 100 % urban area connected to an important number of industries. Therefore, the quality of wastewater is more concentrated in organic matter and hazardous substances. Similarly, although Gafsa WWTP is connected to slightly more people (184,000) than Nabeul SE4 (172,800), it can be noticed that the latter has higher impact. Actually, Nabeul SE4 WWTP treats 16,538 m^3 daily against 10,386 m^3 in Gafsa WWTP. Therefore, the quantity of treated wastewater and electricity consumption all contribute to a higher environmental burden from Nabeul SE4 WWTP. Thus, it can be concluded that the environmental damage of a WWTP depends on the quality and quantity of treated wastewater as well as the size of the plant and intensity of the treatment processes used.

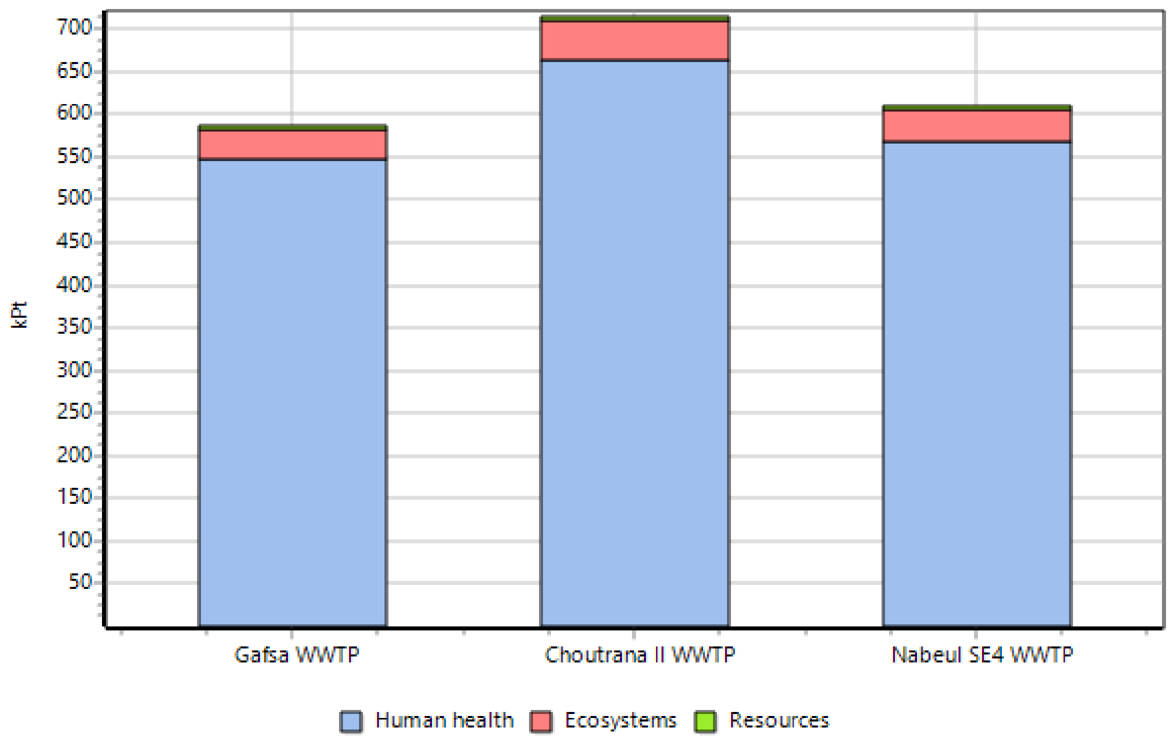

Figure 5- 7: Single score impact results from the different plants

Besides, for a population of 866,838 Nabeul governorate has 19 WWTPs. While Gafsa governorate has only 2 WWTPs for a population of 354,169. These results reflect the previously cited issue of unbalance in wastewater treatment and sanitation services between regions especially north coastal regions and interior regions [49]. Even though the government and the responsible institutions like ONAS are working on solving this problem by planning the creation of more WWTPs in interior regions, it is still very challenging to make such a balance between regions for many historical reasons. The results also lead to understand that the north and coastal regions are the place where most of the emissions of the country are generated not only because of the existence of more industries there, but also because of the significant number of WWTPs. Consequently, emissions from wastewater treatment and biogas become more threatening for people living in those areas especially because the population density in north and coastal regions is much higher than interior regions. Additionally, the north of Tunisia is humid and where more precipitation occurs and hence, it is the area for most of the agricultural and marine activities and farms. Therefore, the impact on resources and ecosystems is severer and negatively influences the country's products quality, availability and resources and exportation activities. Investing in technologies that help to limit emissions from wastewater treatment and biogas should also be on the top priority list of ONAS especially for the plants in north and coastal regions. Working on emissions management from wastewater treatment sector can not only limit air pollution but also preserve the good conditions for other fields like agriculture on which the country relies strongly. This leads again to conclude that emissions policies should be revised, and emissions quotation should be stricter in specific areas.

5.3.4. Uncertainty and sensitivity analysis

In an LCA study, it is necessary to perform a sensitivity analysis to understand the influence of data quality on the variation of the outputs (ref). In this research, sensitivity and uncertainty were performed through Monte Carlo Simulation with a normal distribution of the inputs (CO_2, CH_4, NO_2 and material inputs of each process) and a confidence interval of 95% for 100 iterations for the total environmental damage (sum of the 3 damage categories: human health, ecosystems, resources).

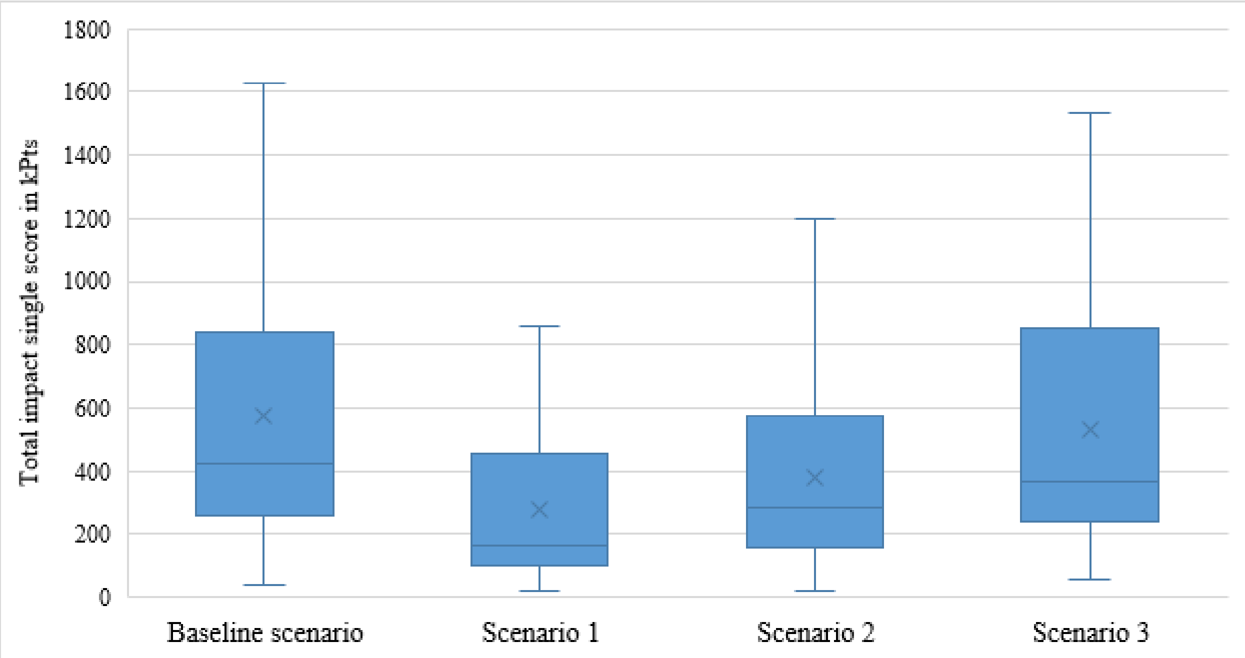

Figure 5- 8: Uncertainty results of total environmental impact of each scenario (kPts)

The results in Figure 5-8 show that the baseline scenario and scenario 3 have the most significant uncertainty margin. This can mean that for the sludge landfill, the only process that exists exclusively in the baseline scenario, emission data (especially nitrogen oxides) is associated with the highest variation. Scenario 3 has a large variation margin, which can be explained by the absence of the electricity consumption process, which is the only process found on Ecoinvent 3 with specific data for Tunisia and, consequently, more accurate emissions data from this process. Additionally, in scenario 3, the amount of electricity generated by cogeneration is higher, resulting in more elevated fossil CO_2 emissions, and therefore the uncertainty from this scenario is higher. Furthermore, the uncertainty in the 4 scenarios can also be explained by the uncertainty associated with biogas-related processes like biogenic CH_4 emissions data, which are not accurate for the case of Tunisia since it is still not used in many plants in the country.

5.4. Conclusion

This study evaluated the impact on the environment of a WWTP in Tunisia using LCA by analyzing the plant's performance under the present conditions and then comparing it to alternative scenarios. Results showed that the highest impact of the plant is from wastewater treatment and sludge landfill, especially in the human health damage category (95% of the total impact). Electricity consumption of the plant does also affect human health. The damage caused by the construction and demolition of the plant is negligible compared to the other processes. The study also suggested substitutional scenarios; anaerobic digestion, cogeneration, and sludge drying. Comparing the baseline scenario to alternative scenarios showed that all the scenarios with anaerobic digestion and sludge drying had lower damage to human health than the baseline scenario. Using solid waste with sludge in anaerobic digestion does not increase the total impact but can be a solution for solid waste disposal. The scenario where the plant uses all the electricity produced by cogeneration had higher impacts than scenarios with partial electricity production by cogeneration. The least environmentally damaging functioning mode is the one in which electricity is supplied from the national grid, and part of it is produced from cogeneration; municipal solid waste is mixed with sewage sludge, digested sludge is dried and used as agricultural fertilizer. This study revealed the improvements that can be made to optimize the performance of WWTPs in Tunisia regarding environmental impact mitigation. It suggested alternative wastewater treatment and sludge management processes for better efficiency and various uses. It also provided insight and motivation for decision-makers to work on solving the obstacles hindering the launch of biogas production projects in Tunisia and widening its use in the whole country. That highlights the environmental benefit of producing biogas and points to the need to revise the current policies related to renewable energy integration and GHG emissions regulations. Prioritizing environmental issues is mandatory in Tunisia and all the countries of the MENA region, primarily because of its current position regarding the effects of climate change. Such a shift toward better environmental decisions will lead countries like Tunisia to achieve their sustainable development goal.

6. Conclusions & Implications

6.1. Conclusion of the study

Switching to renewable energy sources is important for environmental reasons especially with the increasing rate of climate change phenomenon and its effects all over the world. It is however mandatory to ensure that these renewable sources induce the least damage to the environment especially in terms of GHG emissions.

GHG emissions from energy systems are an ongoing research topic even for renewables. Particularly, although biogas production is a good solution to use sludge generated from wastewater treatment, it results in considerable emissions contributing significantly to the total emissions from energy sector in a country. Tunisia is one the countries aiming at increasing biogas production in wastewater treatment plants as a future plan. Having several problems in the waste and wastewater management sector already, it is necessary to study future emissions scenarios and explore optimization options.

This thesis focused on emissions from wastewater and biogas energy systems in Tunisia pointing to the seriousness of this problem. It is the first study to focus on biogas related emissions for the case of Tunisia and its neighbor MENA countries.

The first topic focused on the collection and analysis of existent knowledge related to emissions from wastewater treatment and biogas. That was done through a systematic review on the two largest databases Scopus and Web of Science following several steps of selection criteria. The systematic review allowed to obtain papers with most pertinent and recent results regarding this topic. Most of the studies were done for developed countries case studies and the number of publications increased through the recent years. The analysis of the papers revealed that the most important emissions sources were aerated activated sludge tanks during wastewater treatment process pointing to the need of more focus on the wastewater line improvement. Emissions occur also from digestion tanks because of its leakages and effluent emphasizing on the importance of digester continuous maintenance. Biogas upgrading can also be an important source of emissions especially when energy extensive technologies are used such as high-pressure water scrubbing. The sources, however, differed from one study to another depending on the considerations and assumptions made by the authors or the standard followed. They can therefore be more or less different leading to different conclusions and opinions about the impact of biogas. Authors used various methods to estimate emissions from wastewater treatment and biogas particularly mathematical models, countries specific national standards and international standards like IPCC guidelines, carbon footprint analysis, on-site measurements. The choice of the method depends on the resources available at the plant and needs a planned budget. Moreover, results showed that since developed countries have a higher number of large-scale biogas production and more available data, there is consequently better focus on emissions management. The most affected impact categories from biogas are human health, climate change and global warming. Additionally, acidification and eutrophication potentials and ecosystems have been also mentioned in that regard. This topic confirms the necessity of studies about emissions management from wastewater and biogas clarifying new research areas needed to be focused on.

The second chapter was dedicated to introducing Tunisia, the case study of this thesis. This chapter gave the general information about the country as well as the current waste management and wastewater situation and indicators. It then stated the challenges and objectives of the country regarding wastewater treatment as well as current followed policies and regulations.

The second research topic was a prediction of the possible emissions from wastewater-based biogas in all Tunisia in the case biogas production units are installed all over the wastewater treatment plants in the country. The estimation was done using three equations selected from studies found in the systematic review applied to the case of Gafsa WWTP then extrapolated to a national level. The total emissions WWTPs in Tunisia can reach 126.59 kt CO_{2eq}. Results also showed that the most important emissions were nitrous oxides from activated sludge process (43.65 kt CO_{2eq}) followed by electricity consumption emissions (38.57 kt CO_{2eq}) then cogeneration emissions (36.16 kt CO_{2eq}), discharged water (5.30 kt CO_{2eq}), anaerobic digestion (1.50 kt CO_{2eq}) and finally carbon dioxide from activated sludge (1.40 kt CO_{2eq}). These results give an alert that the government should be prepared for the future emissions scenario. It has been shown that there are options to limit these emissions through best practice and previous countries experience. It should however be pointed that the limited data and methods used represented a barrier to achieve the best accurate results. Also, without knowing how these emissions will impact the environment, it is hard to suggest suitable strategies and policies revisions.

Therefore, the third topic focused on assessing the environmental impacts of wastewater treatment in Tunisia. In this chapter the life cycle assessment of the current existing scenario in WWTPs in Tunisia was done. In this scenario traditional wastewater treatment with secondary treatment by activated sludge takes place in the plant and sludge is disposed of in landfills. Results showed that those two processes contribute to most of the plant's emissions

(42.3% and 41.4%) especially on human health damage category. In the other scenarios, anaerobic digestion and sludge drying were introduced. Those considerably reduced the impact of the plant. However, it is better to only produce part of the plant needs from cogeneration and inject the rest of biogas into the national gas grid. Mixing sludge with municipal solid waste transported to the plant did not have significant emissions hence it is recommended to include it in the future strategies. The alternative scenarios were suggested after checking the countries' plans and available resources to improve the wastewater treatment sector.

Additionally, a comparison between the impact of different plants in Tunisia showed that plants in the big cities are more harmful to the environment. Because of their location close to dense populations and agricultural lands those are prioritized to limit this impact.

6.2. Implications of the study

To reach sustainability, it is necessary to assess existing working sectors and seek out new ecofriendly technologies. In particular, the wastewater treatment field in Tunisia has numerous flaws hindering the achievement of its sustainability. Biogas from wastewater represents currently one of the best solutions to reduce impacts and produce energy. It is important however to ensure the start of biogas production is in suitable conditions that respect the environment. Therefore, this thesis served in a first place to revise current knowledge about biogas and wastewater emissions from more advanced experience in this field in terms of emissions sources and estimation methods which would serve as necessary knowledge for planning for new biogas technology practitioners. It also quantified the amount of emissions in Tunisia when biogas is installed in all the WWTPs. Such research showed the processes that need more focus for emissions management like the anaerobic digestion plant that can have leakages and failures leading to hazardous GHG. Therefore, engineers should check those when installing the unit and testing it before launching the production. Also, emissions from activated sludge process can be high but many countries started using anaerobic wastewater treatment plants and technologies that combine wastewater treatment and anaerobic digestion. It is also advised to apply best practice for the other processes even those with minor emissions. This thesis plotted next the impact from current WWTP working mode which confirmed that changes should be made in the wastewater treatment sector in Tunisia especially in terms of wastewater treatment technologies used and replacing sludge landfill by sludge drying. Sludge drying is a beneficial option both environmentally and economically.

This thesis represents an explorative study of the biogas technology in Tunisia. It supports at the same time widening biogas use and managing its emissions. It also highlights the areas of improvement of the wastewater treatment sector to make it less harmful for the environment. The particularities of this study can be applied also in the case of the other MENA countries since they all share similar climate, political and economic situations and waste management problems. By solving environment related problems, Tunisia and MENA countries can achieve better life quality as well as less risks related to climate change and global warming.

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Appendix A

Table A 1: Emissions off-site emissions from electricity

The annual quantity of electricity consumed by the WWTP (kWh/year) (C_{elect})	1,924,286
the annual average of CO_{2eq} emission factor for the electricity in the year y ($kgCO_{2eq}/kWh$) (EF_{elect})	0.57
Annual GHG emissions associated with electricity consumption ($kgCO_{2eq}$/year) (CO_{2elect})	1,096,843.02
Number of population connected to the wastewater treatment network	6,470,000
Country annual GHG emissions associated with electricity consumption in the year y ($ktCO_{2eq}$/year) (CO_{2elect})	38.57

Table A 2: Emissions from activated sludge process

total organics in wastewater in inventory year, kg BOD/year, for income group i (TOW_1)	2,225,770
emission factor, kg CH4/kg BOD (EF)	0.018
organic component removed from wastewater in aerobic treatment plants, kg BOD/year ($S_{aerobic}$)	2,137,075
amount of CH4 recovered from activated sludge, in inventory year, kg CH4/year (R)	0
CH4 emissions from activated sludge, in inventory year, kg CH4/year ($CH_{4actslu}$)	1,596.51
CH4 emissions from activated sludge, in inventory year, kt CO_2/year	0.04
country CH4 emissions from activated sludge, in inventory year, kt CO_2/year	1.40

Table A 3: Emissions from cogeneration

mass of CH_4 production in the digester (kg CH_4/day) (CH_{4prod})	373,988
Daily CO_2 production resulting from methane combustion (kg CO_2/day) (CO_{2comb})	1,028,467
CO_2 production resulting from methane combustion ($ktCO_{2eq}$/year)	1.03
Country annual CO_2 production resulting from methane combustion ($ktCO_{2eq}$/year)	36.16

Table A 4: Emissions from anaerobic digestion

mass of organic waste treated kg/year (M)	2,137,075
emission factor, kg CH_4/kg BOD (EF)	0.0008
amount of CH_4 recovered from anaerobic digestion, in inventory year, kg CH_4/year (R)	0
CH_4 emissions from anaerobic digestion, in inventory year, kg CH_4/year ($CH_{4actslu}$)	1,709.66
CH_4 emissions from anaerobic digestion, in inventory year, kt CO_2/year	0.04
national CH_4 emissions from anaerobic digestion, in inventory year, kt CO_2/year	1.50

Table A 5: Emissions from discharged water

total organics in wastewater in inventory year, kg BOD/year ($TOW_{effluent}$)	88,695
emission factor, kg CH_4/kg BOD (EF)	0.068
organic component removed from wastewater in water discharge, kg BOD/year ($S_{aerobic}$)	0
amount of CH_4 recovered from discharged water, in inventory year, kg CH_4/year (R)	0
CH_4 emissions from discharged water, in inventory year, kg CH_4/year ($CH_{4actslu}$)	6,031.26
CH_4 emissions from discharged water, in inventory year, kt CO_2/year	0.15
country CH_4 emissions from discharged water, in inventory year, kt CO_2/year	5.30

Table A 6: Nitrous oxide emissions of the plant

annual per capita protein supply, kg protein/person/year	36.13
Fraction of protein consumed	0.9
annual per capita protein consumption, kg protein/person/year (Protein)	32.517
human population who are served by the treatment, person/year (P)	184,000
fraction of nitrogen in protein, default = 0.16 kg N/kg protein (Fnpr)	0.16
factor for nitrogen in non-consumed protein disposed in sewer system, kg N/kg N (Fnon-con)	1.06
factor for industrial and commercial co-discharged protein into the sewer system, kg N/kg N (Find-com)	1.25
additional nitrogen from household products added to the wastewater, default is 1.1 (Nhh)	1.13
total nitrogen in domestic wastewater in inventory year (kg N/yr) (TN)	1,433,318.14
fraction of population in income group in inventory year (U)	0.34
degree of utilization of treatment (T)	0.34
emission factor for treatment (EF) (kg N_2O-N/kg N)	0.016
N2O emissions from domestic wastewater treatment plants in inventory year (N_2Oplants) (kg N_2O/year)	4165.96
N2O emissions from domestic wastewater treatment plants in inventory year (kg CO_{2eq}/year)	1241455.98
N2O emissions from domestic wastewater treatment plants in inventory year (ktCO_{2eq}/year)	1.24
Country annual N2O emissions from domestic wastewater treatment plants (ktCO_{2eq}/year)	43.65

Table A 7: Emissions from electricity consumption in case 2

Volume of methane (m^3)	557,359.17
Electricity production (kWh)	1,672,077.50
the annual average of CO2eq emission factor for the electricity in the year y ($kgCO_{2eq}$/kWh) (EFelect,y)	0.57
the quantity of electricity consumed by the WWTP in the year y (kWh/year) (Celect,y)	252,208.50
GHG emissions associated with electricity consumption in the year y ($kgCO_{2eq}$/year) (CO_2elect,y)	143,758.85
GHG emissions associated with electricity consumption in the year y ($ktCO_{2eq}$/year) (CO_2elect,y)	0.14
GHG emissions associated with electricity consumption in the year y ($ktCO_{2eq}$/year) (CO_2elect,y)	5.05

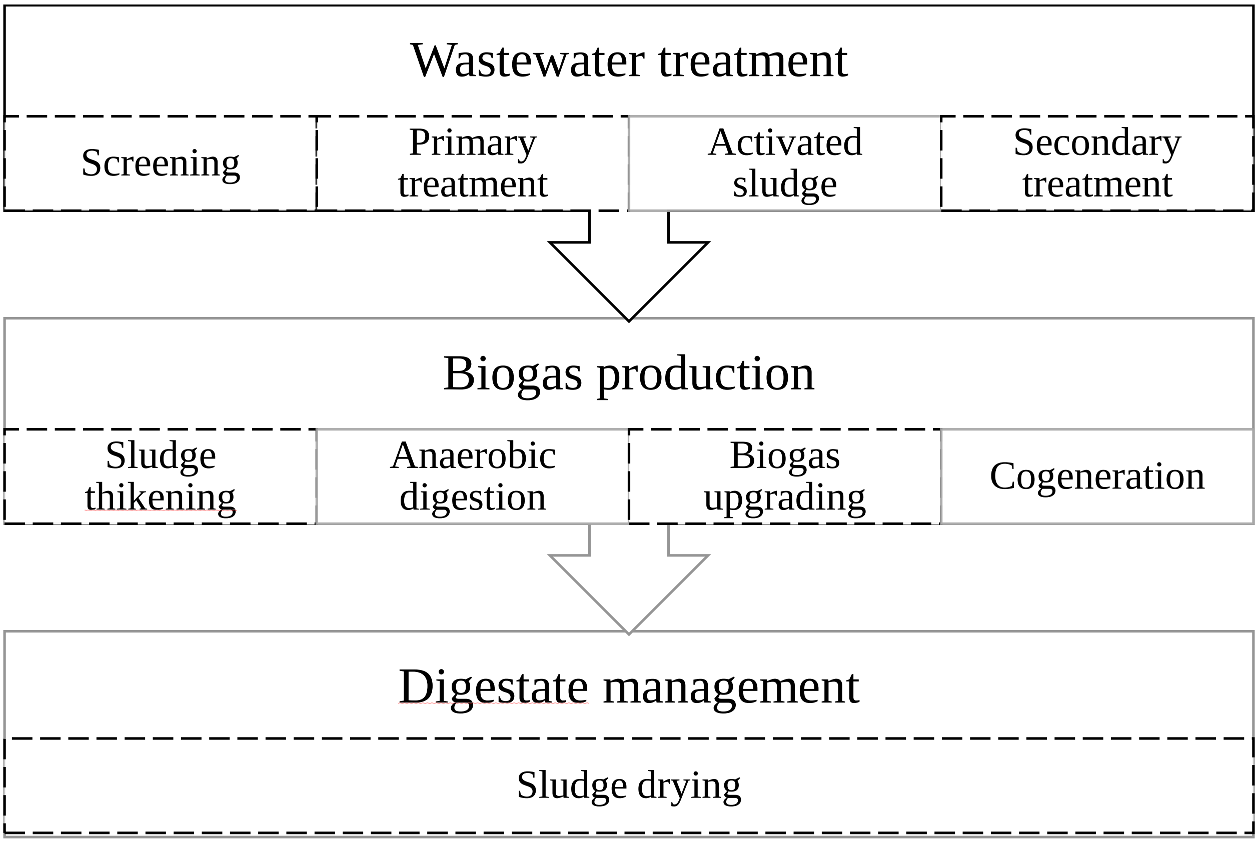

Figure A 1: Flow diagram of processes taking place inside Gafsa WWTP and study boundaries

The figure above represents the flow of the processes in Gafsa WWTP. The processes in dashed rectangles are not included in this study.

Appendix B

Table B 1: Wastewater treatment plants in Tunisia: name, starting year, capacity and regional distribution

WWTP location	Starting date	Treatment capacity (m^3/day)	Region	Size classification	Region population	Region latitude and longitude
Choutrana I	1986	78,000	Ariana	Large scale	667,354	36.8665° N, 10.1647° E
Kalaat El Andalous	1994	1,500		Medium scale		
Choutrana II	2008	40,000		Large scale		
Chorfech	2009	25		Small scale		
Sidi Omar	2017	520		Small scale		
Kantret Binzart	2018	200		Small scale		
Beja	1994	14,000	Beja	Large scale	308,148	36.7333° N, 9.1844° E
Medjez El Bab	1994	4,500		Medium scale		
Teboursouk	2000	1,280		Medium scale		
Testour	2004	1,180		Medium scale		
Oued Zargua	2003	30		Small scale		
Nefza	2006	1,500		Medium scale		
Sud Meliane I	1982	37,500	Ben Arous	Large scale	715,490	36.7435° N, 10.2320° E
Industrial WWTP	2001	5,500		Medium scale		
Mornag	2004	3,200		Medium scale		
Sud Meliane II	2007	40,000		Large scale		
Bizerte	1997	26,600	Bizerte	Large scale	597,490	37.2768° N, 9.8642° E
Menzel Bourguiba	1997	11,065		Large scale		
Mateur	2005	4,100		Medium scale		
Aousja	2010	9,100		Medium scale		
Gabes	1995 renewed in 2017	22,100	Gabes	Large scale	404,829	33.8881° N, 10.0975° E
El Hamma Gabes	2004	4,061		Medium scale		
Metouia-Ouedhref	2007	2,700		Medium scale		
Mareth- Zaraat	2007	2,860		Medium scale		

Gafsa	1985 renewed in 2020	13,928	Gafsa	Large scale	354,169	34.4311° N, 8.7757° E
Metlaoui	2006	4,078		Medium scale		
Tabarka	1993	5,500	Jendouba	Medium scale	404,738	36.5072° N, 8.7757° E
Jendouba	1994	8,000		Medium scale		
Bou Salem	2000	2,730		Medium scale		
Fernana	2003	270		Small scale		
Ghardimaou	2003	1,882		Medium scale		
Ain Drahem	2017	1,074		Medium scale		
Hammem Bourguiba	2010	230		Small scale		
Tabarka Airport	1995	100		Small scale		
Hajeb El youn	2006	2,020	Kairouan	Medium scale	599,560	35.6712° N, 10.1005° E
Bouhajla	2006	1,343		Medium scale		
Oueslatia	2006	1,020		Medium scale		
Haffouz	2006	1,513		Medium scale		
Kairouan 2	2008	20,000		Large scale		
Kasserine	1994	15,000	Kasserine	Large scale	463,497	35.1723° N, 8.8308° E
Sbeitla	2004	3,870		Medium scale		
Kebili	2002	3,130	Kebili	Medium scale	170,450	33.7072° N, 8.9715° E
Douz	2004	5,364		Medium scale		
El Kef	1998	8,500	Kef	Medium scale	247,289	36.1680° N, 8.7096° E
Jrissa	2015	691		Small scale		
Sers	2016	1,523		Medium scale		
El Jem	1994	1,250	Mahdia	Medium scale	445,704	35.5024° N, 11.0457° E
Ksour Essaf	1994	1,500		Medium scale		
Mahdia	1995	10,220		Large scale		
Boumerdes	2003	700		Small scale		
Chebba	2007	3,500		Medium scale		
Jedaida	2003	2,800	Manouba	Medium scale	423,111	36.8093° N, 10.0863° E
Tebourba	2004	2,825		Medium scale		

Mornaguia	2015	6,060		Medium scale		
Souihel- Zarzis	1980	1,108	Medenine	Medium scale	519,074	33.3399° N, 10.4959° E
Sidi Mehrez-Jerba	1981	3,000		Medium scale		
Lalla Mariem-Zarzis	1982	1,726		Medium scale		
Houmt Souk-Jerba	1991	3,500		Medium scale		
Zarzis ville	1992	1,335		Medium scale		
Medenine	2000	8,870		Medium scale		
Djerba- Aghir	2001	15,750		Large scale		
Djerba- Ajim	2016	2,000		Medium scale		
Monastir-Dkhila	1979	3,100	Monastir	Medium scale	606,401	35.7643° N, 10.8113° E
Moknine	1986	6,400		Medium scale		
Sahline	1993 renewed in 2016	11,370		Large scale		
Ouardanine	1993	1,500		Medium scale		
Sayyada-Lamta-Bouhjar	1993 renewed in 2013	2,160		Medium scale		
Monastir-Frina	1995	13,500		Large scale		
Jammal	2000	6,700		Medium scale		
Beni Hassen	2007	1,584		Medium scale		
Kelibia	1976 renewed in 1997	5,542	Nabeul	Medium scale	866,838	36.4513° N, 10.7357° E
SE4	1979 renewed in 2016	16,538		Large scale		
SE1	1980	4,208		Medium scale		
SE3	1981	3,500		Medium scale		
Soliman 1	1983	2,457		Medium scale		
Grombalia	1993 renewed in 2017	3,082		Medium scale		
Menzel Bouzelfa	1993 renewed in 2015	5,319		Medium scale		
Hammamet Sud	1995	11,386		Large scale		

Korba	2002	7,574		Medium scale		
Khanget El Hojjej	2002	96		Small scale		
Soliman 2	2004	12,300		Large scale		
El Haouaria	2006	1,523		Medium scale		
Bouargoub	2007	2,735		Medium scale		
Mrissa	2009	400		Small scale		
Korbus	2009 renewed in 2017	630		Small scale		
AFH El Mrezgua	2009	2,500		Medium scale		
Beni Ayech	2009	200		Small scale		
Menzel Temime	2014	8,283		Medium scale		
Tazarka-Somaa-Maamoura	2017	7,500		Medium scale		
Sfax Sud	1983 renewed in 2006	49,500	Sfax	Large scale	1,022,900	34.7398° N, 10.7600° E
Mahares	1994	780		Small scale		
Sfax Nord	2004	17,900		Large scale		
El hancha	2005	700		Small scale		
Aguareb	2006	2,030		Medium scale		
Jbeniana	2006	1,312		Medium scale		
Kerkena	2007	2,700		Medium scale		
Sidi Bouzid	1994	3,125	Sidi Bouzid	Medium scale	457,537	35.0354° N, 9.4839° E
Jelma	2010	645		Small scale		
Maknessy	2016	1,362		Medium scale		
Mezzouna	2017	900		Small scale		
Siliana	2000	4,530	Siliana	Medium scale	228,691	36.0887° N, 9.3645° E
Gaafour	2003	1,325		Medium scale		
Bouaarada	2016	1,451		Medium scale		
Makther	2018	1,074		Medium scale		
Sousse Nord I	1978	17,400	Sousse	Large scale	747,887	35.8245° N, 10.6346° E
Sousse Sud	1980	18,700		Large scale		
Sousse Nord II	2010	10,000		Large scale		

Kalaa Sghira	1993	1,450		Medium scale		
Sidi Bou Ali	1996	644		Small scale		
Msaken	1996	7,844		Medium scale		
Enfidha/Hergla	2012	10,450		Large scale		
Sousse Hamdoun	2018	30,000		Large scale		
Tataouine	1999	5,430	Tataouine	Medium scale	151,750	32.9211° N, 10.4509° E
Tozeur	2000	6,654	Tozeur	Medium scale	115,675	33.9185° N, 8.1229° E
Nefta	1992	1,335		Medium scale		
Charguia	1958 renewed in 2002	60,000	Tunis	Large scale	1,075,015	36.8065° N, 10.1815° E
North coastal	1981	15,750		Large scale		
El Attar	2015	60,000		Large scale		
Zeriba	2002	2,000	Zaghouan	Medium scale	190,127	36.4091° N, 10.1423° E
Zaghouan	2005	2,800		Medium scale		
El Fahs	2006	3,350		Medium scale		

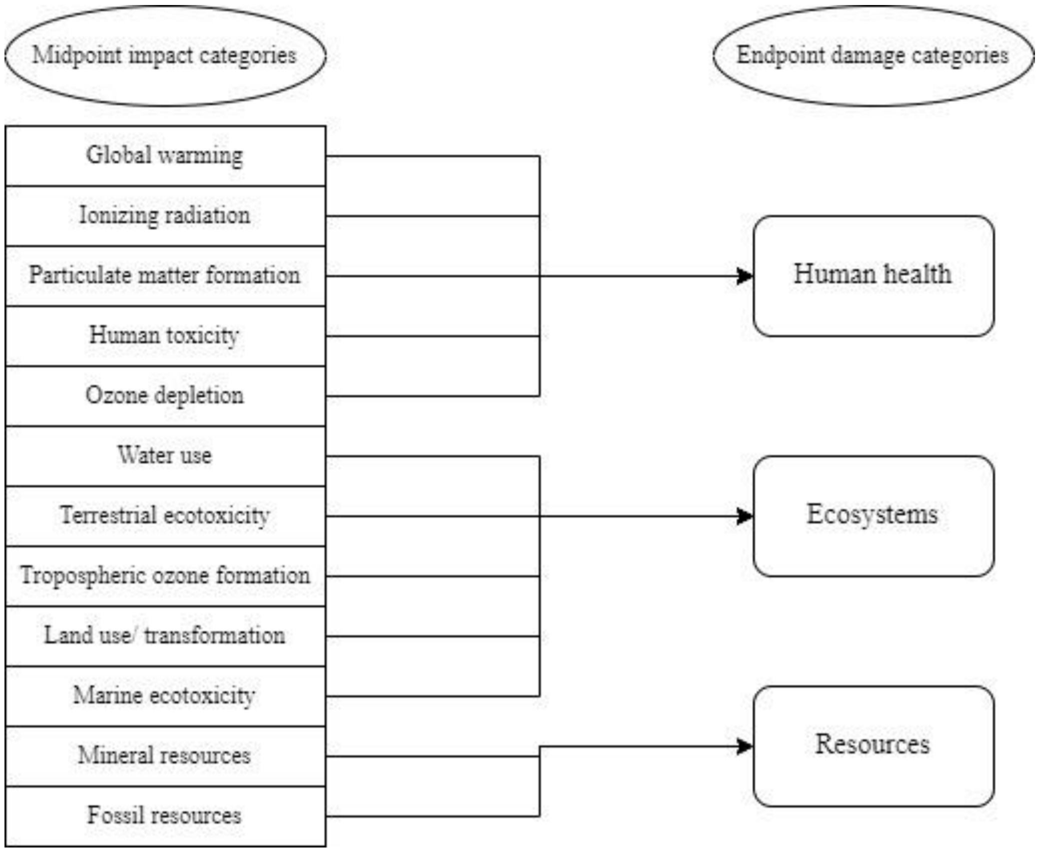

Figure B 1: Relations between Recipe Midpoint impact categories and Endpoint damage categories analyzed in this study

Table B 2: Characterization calculations of the baseline scenario

Impact category	Unit	Total	Construction of the plant	Electricity consumption	Sludge landfill	Wastewater (Wastewater treatment process)	Demolition of the plant
Water consumption, Aquatic ecosystems	species.yr	5.42E-08	6.20E-09	4.22E-09	2.46E-11	4.36E-08	1.97E-10
Global warming, Freshwater ecosystems	species.yr	1.21E-06	7.20E-08	1.56E-07	5.33E-07	4.48E-07	3.39E-09
Marine eutrophication	species.yr	8.15E-06	4.28E-08	1.07E-07	7.63E-06	3.71E-07	5.00E-09
Terrestrial ecotoxicity	species.yr	7.44E-04	1.05E-04	4.10E-06	5.12E-07	6.34E-04	1.93E-07
Marine ecotoxicity	species.yr	4.65E-04	1.75E-05	4.27E-06	3.34E-04	1.08E-04	2.00E-07
Freshwater ecotoxicity	species.yr	2.33E-03	8.97E-05	2.05E-05	1.66E-03	5.57E-04	9.60E-07
Water consumption, Terrestrial ecosystem	species.yr	4.72E-04	5.41E-05	3.41E-05	1.34E-07	3.82E-04	1.60E-06
Land use	species.yr	7.16E-03	4.50E-04	1.49E-04	7.62E-05	6.48E-03	6.98E-06
Ozone formation, Terrestrial ecosystems	species.yr	2.81E-03	3.65E-04	1.56E-04	3.62E-05	2.24E-03	7.31E-06
Stratospheric ozone depletion	DALY	1.51E-03	1.45E-04	1.70E-04	7.02E-06	1.18E-03	7.97E-06
Terrestrial acidification	species.yr	4.66E-03	6.04E-04	5.29E-04	5.48E-05	3.45E-03	2.47E-05
Freshwater eutrophication	species.yr	2.74E-03	2.76E-04	6.66E-04	2.47E-04	1.52E-03	3.11E-05
Ionizing radiation	DALY	1.18E-03	-4.26E-05	8.72E-04	8.84E-07	3.05E-04	4.08E-05
Ozone formation, Human health	DALY	1.89E-02	2.45E-03	1.09E-03	2.51E-04	1.51E-02	5.10E-05
Global warming, Terrestrial ecosystems	species.yr	4.44E-02	2.64E-03	5.70E-03	1.95E-02	1.64E-02	1.24E-04
Water consumption, Human health	DALY	6.72E-02	7.16E-03	5.42E-03	1.30E-05	5.44E-02	2.54E-04
Human carcinogenic toxicity	DALY	2.42	2.46E-01	1.52E-01	3.04E-01	1.71	7.12E-03

Human non-carcinogenic toxicity	DALY	16.08	4.34E-01	2.94E-01	12.76	2.58	1.38E-02
Global warming, Human health	DALY	14.72	8.73E-01	1.89	6.48	5.43	4.11E-02
Fine particulate matter formation	DALY	13.39	1.10	2.37	6.45E-02	9.74	1.11E-01
Mineral resource scarcity	USD2013	57541.22	5216.86	126.07	13.47	52178.93	5.90
Fossil resource scarcity	USD2013	546985.07	52275.40	77240.98	3160.37	410694.09	3614.24