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ABSTRACT: Although significant progress has been achieved in the field of environmental impact assessment in many engineering disciplines, the impact of wastewater treatment plants has not yet been well integrated. In light of this remarkable scientific progress, the outputs of the plants as treated water and clean sludge have become potential sources of irrigation and energy, not a waste. The aim of this study is to assess the environmental impacts of upgrading the wastewater treatment plants from primary to secondary treatment. The Lifecycle Assessment Framework (ISO 14040 and 14044) was applied using GaBi Software. Abu Rawash wastewater treatment plant (WWTP) has been taken as a case study. Two scenarios were studied, Scenario 1 is the current situation of the WWTP using the primary treatment units and Scenario 2 is upgrading the WWTP by adding secondary treatment units. The study highlighted the influence and cumulative impact of upgrading all the primary WWTPs in Egypt to secondary treatment. With the high amount of energy consumed in the aeration process, energy recovery methods were proposed to boost the circular economy concept in Abu Rawash WWTP in order to achieve optimal results from environmental and economic perspectives.

KEYWORDS: ISO 14040 & 14044 LCA framework, upgrading WWTPs, environmental impact assessment, GaBi, recycling, energy recovery

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Introduction

Water sustainability and water stress became important issues for many countries, especially developing ones due to the rapid population growth, as well as the rapid expansion in agriculture and industrial activities.[1] In order for wastewater treatment sector to be sustainable in the long-run, better wastewater treatment system has to be selected, while taking into account the technical and economic constraints, as well as global warming and climate change effects.[2,3] Detailed information on environmental aspects of each treatment system is necessary to provide foundation for better choice.[4,5] Wastewater treatments plants (WWTPs) produce high impacts on the receiving water bodies on both environmental and economic levels.[6] On the other hand, these impacts would be much higher in the absence of the WWTPs. The overall costs and achieved effluent quality depend mainly on the influent type and characteristics, employed treatment technology, and the desired effluent quality.[7]

Life Cycle Assessment (LCA) is an essential step to evaluate the socio-economic, cultural, human health, an environmental impacts associated with the operation of any WWTP. ISO 14040 and 14044 LCA framework have set a methodology for the assessment of the potential environmental impacts that a process may generate over its entire life cycle.[8,9] In LCA of WWTPs, the cradle-to-grave approach is normally applied, which starts from extraction of raw materials and ends in their disposal or recycle.[10,11] Li et al[1] has used LCA approach to assess the drawbacks and the environmental benefits of WWTP in Kunshan, China. The results revealed that improving the effluent quality would have a direct positive impact on the environment, especially when utilizing the renewable energy as a source of power. Zang et al[12] has also reviewed more than 20 studies on LCA dealing with activated sludge WWTPs in order to provide qualitative interpretation for the most important environmental categories associated with wastewater treatment; global warming potential (GWP), land use, energy balance, eutrophication potential, water use, toxicity-related impacts, and other impact categories. Garfí et al[13] has focused their research in small communities by conducting a comparison between activated sludge system and two nature-based technologies (high rate algal pond and hybrid constructed wetland systems) using LCA approach. His paper concluded that nature-based solutions are the more environmentally friendly options to conventional one due to the low chemicals and electricity consumption. Awad et al[14] has investigated the environmental impacts of four scenarios to improve WWTPs and has found that the energy consumption has a major impact on the environment. Also, Yacout[15] has assessed the LCA in Egypt.

Many literature are available on utilizing LCA to evaluate wastewater treatment systems, some of these literature and relevant studies were listed in Table 1. These studies demonstrated that there is a significant impact on the environment especially in the form of energy-orientation. Attention shall be

Table 1. List of previous studies.

REFERENCE	YEAR	DESCRIPTION
Teodosiu et al[16]	2016	Environmental assessment of municipal wastewater discharges: a comparative study of evaluation methods
Zang et al[12]	2015	Review toward more accurate life cycle assessment of biological wastewater treatment plants
Lane et al[17]	2015	LCA of urban water systems in Australia
Mills et al[18]	2014	LCA evaluation of sludge treatment technologies in United Kingdom
Corominas et al[19]	2013	Extensive review for LCA of wastewater methodologies
Mahgoub et al[20]	2010	LCA urban water system in Alexandria, Egypt

Abbreviation: LCA, Life Cycle Assessment.

Table 2. Comparative assessment between three LCA software.

CRITERIA	GABI	SIMAPRO	OPENLCA
Presentation of results	Obtain diagrams and bar charts to show LCA results. Automatic flow balances and tables are utilized for inventory analysis.	Obtain diagrams and bar charts to show LCA results. Tables are utilized for inventory analysis.	Obtain diagrams and bar charts to show LCA results. Tables are utilized for inventory analysis.
Uncertainty and sensitivity analysis	Monte Carlo method is used for sensitivity analysis. Scenario analysis can be made. Percentage deviations can be used for inventory flows.	Monte Carlo method is used for sensitivity analysis. Scenario analysis can be made.	Monte Carlo method is used for sensitivity analysis. Scenario analysis can be made.
Advantages	GaBi has its own professional database, which is very reliable and contains more than 4500 Life Cycle Inventory. Also, It can work with external databases. It is possible to import and export databases.	External Database shall be imported. It is possible to import and export databases.	External Database shall be imported. It is possible to import and export databases.
Disadvantages	Higher cost of investment	Limited number of dataset formats	Lack of freely available datasets. Many datasets are poorly documented.

Abbreviation: LCA, Life Cycle Assessment.

directed toward advanced technologies of wastewater treatment and to be able to remove the evolving pollutants.[7,12,19]

In order to select a software to conduct this study, a comparative assessment has been undertaken to compare between three well-known LCA softwares, which are (1) Gabi, (2) Simapro, and (3) OpenLCA as shown in Table 2. The comparison has demonstrated that the three software are reliable and obtain close results. However, GaBi has the advantage of having its own professional database, which is very reliable and contains more than 4500 Life Cycle Inventory. This will facilitate the modeling process. In addition, GaBi facilitates using the sensitivity analysis percentage deviations for inventory flows.

The aim of this study is to assess the environmental impacts of the wastewater treatment plants using Abu Rawash WWTP as a case study, specifically the principles and framework methodology of life cycle assessment of the plants, and then develop an assessment approach in the typical wastewater treatment plants. The Lifecycle Assessment Framework (ISO 14040 and 14044) was applied using GaBi Software to study the environmental impacts resulting from construction and operation until the end of the life of the treatment plant.[8,9] GaBi has been utilized in this study, to assess the various environmental parameters and indicators such as global warming and climate change potential, ozone depletion, soil and water acidification, terrestrial and water eutrophication, photochemical ozone production, and human and eco-toxicity. Two scenarios were examined under this study.[21] The first scenario is studying the environmental impacts of the plant in its current situation using the primary treatment units and the second scenario is studying the impact of the inclusion of secondary treatment units. It is worth mentioning that the existing treatment plant is designed to accommodate 1.2 million cubic meters per day of untreated wastewater. From the site sample, it was found that the proportion of sludge volume ranges from 20% to 30%. Scenario 2 was designed to accommodate 1.6 million cubic meters per day of untreated wastewater. This scenario includes the inclusion of additional primary sedimentation tanks, aeration tanks (activated sludge), final sedimentation tanks and chlorinated disinfection tanks for the production of high

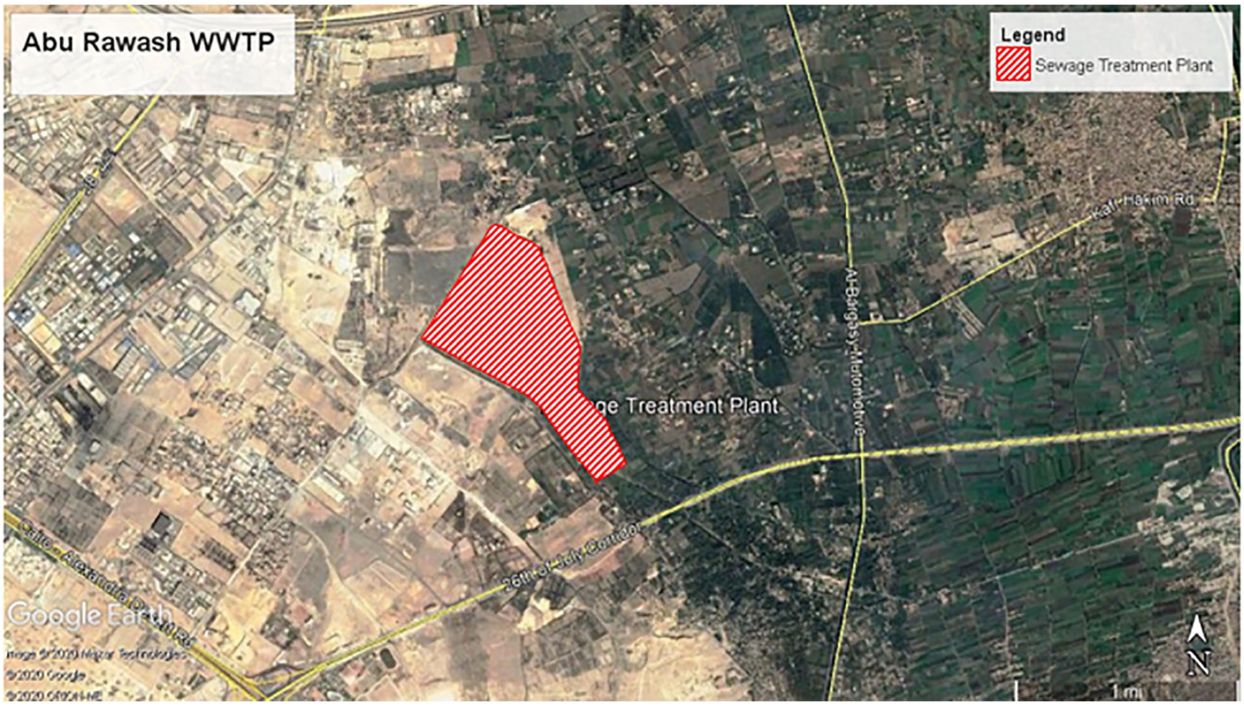

Figure 1. Abu Rawash WWTP location. WWTP indicates wastewater treatment plant.

quality treated wastewater suitable for irrigation and agriculture purposes.

It is worth to note that the aeration tanks will require a huge amount of energy. In the light of this, the study comprised a business model and economic approaches for recovering energy from wastewater and upgrading biogas to bio-methane were studied. Recovering energy from wastewater have become a necessity to optimize the enormous amount of electricity consumed in the WWTP, especially by the aeration tanks. Human waste and wastewater represent resources that can be source to generate economic and environmental revenue by using them to generate energy. The reduction, removal, and reuse of wastes must become financially viable and economically profitable. Resource Recovery and Reuse (RRR) is considered one of the successful, innovative, and sustainable business models that helps to achieve an efficient circular economy.[22] RRR shall be used to transform "pollution" into assets in which the smart political leaders can accept voluntarily for benefit sharing across sectors and actors.

Methodology

This section presents the methodology adopted in this study, to estimate the environmental impact assessment of Abu Rawash WWTP. The methodology comprises six main steps including reviewing the available literature of the studies that utilized the same approach and collecting all the required data about the software and Abu Rawash WWTP. Then, the LCA framework (ISO 14040 and 14044) has been adopted through 4 phases which are as follows: (1) goal and scope definition, (2) inventory analysis, (3) life cycle impact assessment, and (4) interpretation.[8,9] After having all the required data and information available, GaBi software has been introduced to model the different scenarios and obtaining results, which have been analyzed and interpreted.

Data collection

After having the available literature review under the introduction section, data about the influent and effluent water quality, treatment procedures and capacity of the two scenarios of Abu Rawash WWTP, as a case study, have been collected. Abu-Rawash WWTP is located at the west bank area of Cairo on approximate area is 104 hectares as shown in Figure 1. Abu Rawash WWTP was initially designed to be constructed in phases according to the growth of the catchment population. The first stage was designed as a primary treatment system and had a capacity of 0.4 x 10^6 m^3/day. Then, it was expanded to reach its current capacity of 1.2 x 10^6 m^3/day. However, the current inflow into the plant exceeded the capacity by almost 0.4 million m^3/day. Accordingly, the quality of the effluent was deteriorated. With the continuous increase in population and demand, the effluent from the WWTP is utilized for agriculture even though the risks to the public health and the violation to the Egyptian laws.[23,24] A further expansion was designed to accommodate 1.6 x 10^6 m^3/day by adding a secondary treatment system as shown in Figure 2. This expansion aims to bring down the effluent quality to acceptable limit for reuse in agriculture.

Table 3 shows the current and future design capacities of the WWTP in required to contain the inflow wastewater. Also, the design flow and other parameters of Abu Rawash WWTP are presented in Table 4.

Figure 2. Satellite image for the existing condition and proposed future expansion area.

Table 3. Current and future population, inflow wastewater, and required design capacity.[23]

ITEM	UNITS	2017	2027
Population	Capita	3.44 x 10^6	4.06 x 10^6
Inflow wastewater	m^3/day	1.35 x 10^6	1.64 x 10^6
Design capacity	m^3/day	1.2 x 10^6	1.6 x 10^6

LCA framework

Goal and scope definition. The study comprises a comparison between two scenarios. Scenario 1, the existing situation of providing only primary treatment. Scenario 2, by adopting secondary treatment units at Abu-Rawash WWTP. This analysis assumed that a 1 m^3 of treated wastewater as a functional unit. The analysis considered the environmental records of the material production, transportation, construction, and operation activities for wastewater treatment plant, covering the whole life cycle from cradle to operation (cradle-to-gate analysis).

Scenario 1, the existing WWTP, was designed to handle a flow of 1.2 x 10^6 m^3/day of untreated wastewater influent, including screening for removal of rags, large solids, and debris; grit removal chamber which are used to collect sand, small stones, cinders, and grit that have passed through screens through reducing the velocity of the sewage and thus allow heavy particles to settle to the bottom, in addition to the air induced through the chamber to allow oil to float on the surface of the oil separator tank; and primary sedimentation tanks that are used to reduce organic loading by settling suspended solids and floatable materials.

Table 4. Design flow and other parameters of Abu Rawash WWTP.

ITEM	UNITS	VALUES
a. Flow rate and raw sewage characteristics		
Daily average	m^3/day	1.2 x 10^6
Daily maximum	m^3/day	1.44 x 10^6
Peak flow	m^3/day	1.8 x 10^6
Turbidity (raw sewage)	NTU	38
pH (raw sewage)		7.2
DO (raw sewage)	mg/L	0.35
BOD (raw sewage)	mg/L	165
TSS (raw sewage)	mg/L	350
COD (raw sewage)	mg/L	210
b. Design values and removal ratio		
BOD removal ratio (primary treatment)		50%
TSS removal ratio (primary treatment)		60%
c. Treated effluent		
BOD	mg/L	99
TSS	mg/L	114
pH		7.45
DO	mg/L	0.95
COD	mg/L	210
Turbidity	NTU	19

Abbreviations: BOD, biological oxygen demand; COD, chemical oxygen demand; DO, dissolved oxygen; TSS, total suspended solids; NTU, Nephelometric Turbidity Units; WWTP, wastewater treatment plant.

Scenario 2, the future expansion of the WWTP, was designed to handle 1.6 x 10^6 m^3/day of untreated wastewater influent. Additional primary sedimentation tanks, aeration tanks (activated sludge), final sedimentation tanks, and chlorination contact tanks are proposed to be installed in order to produce higher quality treated sewage effluent that can be utilized for irrigation purposes and the sludge can be used for agricultural application. Figure 3 shows the main components and the treatment process of the two Scenarios 1 and 2, which will be inputs to GaBi.

Gabi LCA built-in database has been utilized for the life cycle inventory. The GaBi software is accompanied by a wide-ranging, up-to-date Life Cycle Inventory database available. GaBi Database contains over 4500 Life Cycle Inventory datasets based on primary data collection.[21,25] The ReCiPe method was selected as the life cycle impact assessment method, which comprises harmonized category indicators at the midpoint and the endpoint level.[26]

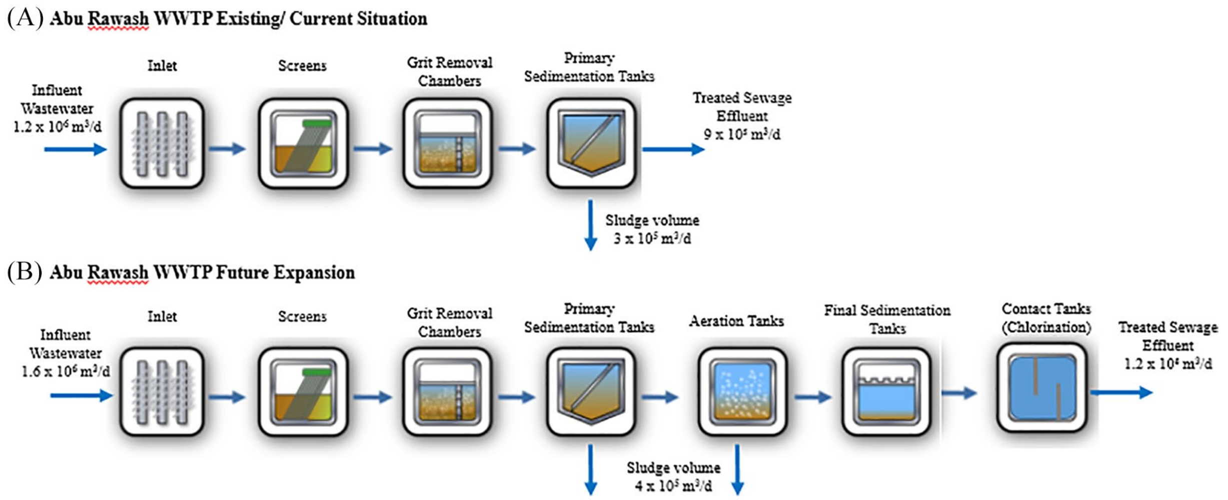

Figure 3. Wastewater Treatment Process for two scenarios: (i) Scenario 1 and (ii) Scenario 2. (A) Abu Rawash WWTP Existing/Current Situation. (B) Abu Rawash WWTP Future Expansion. WWTP indicates wastewater treatment plant.

Life Cycle Inventory analysis. Life cycle inventory has been analyzed to present the influent and effluent, in addition to the energy consumption.[27] Table 5 shows the inventory of the components of Abu Rawash WWTP per cubic meter. Some assumptions were considered in this analysis and can be summarized in the following sections.

Life Cycle Assessment. The LCA aims at studying the potential environmental impacts of the product or service throughout its life cycle. The cradle-to-gate principle studies all the processes that a material or a service passes through starting from (1) its extraction and acquisition as a raw material, (2) its transportation, (3) its construction process, and (4) its operation process.[8,9] This process is taking into consideration the human health and ecological concerns as shown in Figure 4.

GaBi software description. GaBi Software is a Leading Life Cycle Assessment Software, which has a numerous number of applications. The software uses the Life Cycle Assessment to design products for low environmental impact, improve efficiency, or develop profiles of your carbon, water, and product environmental footprints. It assesses all product, processes, and raw materials in every phase, from extraction to End-of-life. GaBi LCA built-in database has been utilized for the life cycle inventory. GaBi software is accompanied by a wide-ranging, up-to-date Life Cycle Inventory database available. This available database contains over 4500 Life Cycle Inventory datasets based on primary data collection.[21,25] ReCiPe method has been utilized to obtain the various environmental impact indicators used in this study at midpoint level. Table 6 shows the units of estimation for these environmental impact indicators.[26]

Model building and analysis. Figures 5 and 6 show the building components of the model as extracted from GaBi, in addition to the linkage between the different elements and processes for Scenarios 1 and 2, respectively. Each model has the input and output water quality, construction components, transportation and electricity parameters included.

Results and Analysis

This section presents the results of the assessment conducted for Abu Rawash WWTP for the two Scenarios 1 and 2. Also, it evaluates and discusses the various environmental impact indicators used in this study in the following subsections: (1) GWP and climate change, (2) ozone depletion, (3) soil and water acidification, (4) terrestrial and aquatic eutrophication, (5) photochemical ozone production, (6) human and eco-toxicity, (7) resources and water depletion, and (8) abiotic depletion potential.

GWP and climate change

GWP is the measure of the amount of greenhouse gases entrapped in the atmosphere. It estimates the energy absorbed during the emission of a gas over a certain period of time in terms of the amount of carbon dioxide (CO_2) that results in absorption of the same amount of energy during emission. GWP and climate change are presented in CO_2 equivalents (kg CO_2 eq.). A 100-year period was used in the model calculations as the residence time of gases in the atmosphere.[28]

The GWP value resulted from treating 1 m^3 of wastewater in the current situation was found to be 0.805 kg CO_2 eq, while it was slightly increased to 0.969 kg CO_2 eq in the future expansion scenario as shown in Figure 7. It is also worth noting that the GWP values for both scenarios are relatively close yet Scenario 2 is higher and this is mainly due to the large amount of electricity consumed in the treatment process.

Ozone depletion potential

Ozone depletion potential (ODP) is estimated by reaching an equilibrium state of total ozone reduction. Chlorofluorocarbon

Table 5. Inventory of the components of Abu Rawash WWTP per cubic meter wastewater.

PARAMETER	UNIT	VALUE	PARAMETER	UNIT	VALUE	
A. INFLUENT			B. EFFLUENT		SCENARIO 1	SCENARIO 2
Flow Scenario 1 Scenario 2	m^3/day	 1.20 x10^6 1.60 x10^6	Flow	m^3/day	1.20 x 10^6	1.60 x 10^6
Biological oxygen demand (BOD_5)	mg/L	165	BOD_5	mg/L	140	35
Suspended solids (SS)	mg/L	350	SS	mg/L	150	30
Chemical oxygen demand (COD)	mg/L	210	COD	mg/L	170	70
Ammonia-nitrogen (NH_3-N)	mg/L	1.2 x 10^{-4}	NH_3-N	mg/L	4.8 x 10^{-6}	8.2 x 10^{-9}
pH	-	7-8	pH	-	7.4	7.4
A.1 Electrical power			B.1 Sludge			
Electricity consumption	MJ	1.45	Production of Sludge	T	4.5	7.5
A.2 Chemical additives			B.2 Trace Elements Emissions to soil			
Iron chloride	kg	6.26 x 10^{-6}	Nitrogen (N)	kg	1.6 x 10^{-4}	2.6 x 10^{-2}
Phosphoric acid	kg	0.0571	Phosphorus (P)	kg	1.8 x 10^{-5}	1.5 x 10^{-3}
A.3 Construction materials			Potassium (K)	kg	1.7 x 10^{-5}	2.3 x 10^{-3}
Cement	kg	650	Cadmium (Cd)	kg	1.35 x 10^{-5}	1.59 x 10^{-3}
Metal	kg	32	Chromium (Cr)	kg	1.5 x 10^{-6}	3.6 x 10^{-4}
Transportation	km	10	Copper (Cu)	kg	1.2 x 10^{-6}	1.6 x 10^{-4}
			Lead (Pb)	kg	1.2 x 10^{-6}	1.6 x 10^{-3}
			Zinc (Zn)	kg	2.1 x 10^{-6}	1.3 x 10^5
			Nickel (Ni)	kg	3.7 x 10^{-7}	2.1 x 10^{-6}
			Lead (Pb)	kg	1.2 x 10^{-6}	2.6 x 10^{-2}

Abbreviation: WWTP, wastewater treatment plant; MJ, MegaJoule

(CFC 11) is replaced by the quantity of each life cycle phase of the components involved in the construction of the retaining walls involved in this study. This leads to the ODP for each substance taking into consideration the long-term, global and partly irreversible effects. ODP is presented in equivalents of CFC 11.[29]

In Scenario 2, during the aeration process, a large amount of electrical energy will be consumed resulting in increase in ozone depletion as a result of increase in CFC 11 eq. Therefore, the ODP in the future expansion scenario was found to be significantly higher compared to the original situation with values of 4.82E-10 and 8.31E-14 kg CFC 11 eq, respectively, as shown in Figure 8

Soil and water acidification

Soils and waters acidification occurs mainly through the transformation of air pollutants into acids and is estimated in Sulfur dioxide equivalents (SO_2 eq.). This results in a decrease in the pH-value of rainwater from 5.6 to 4.0 and less. Sulfur dioxide and nitrogen oxide and their acidic forms contribute in the damages of the terrestrial ecosystems. For instance, acidification causes metals and stones to corrode at an increased rate.[30]

Therefore, Scenario 2 has resulted in larger acidification potential (AP) as it contains additional aeration tanks. During the aeration process, a large amount of electrical energy is consumed resulting in increase in acidification of soil and water. Soils and waters acidification occurs mainly through the transformation of air pollutants into acids. For the same reason, the soil and water acidification has increased from 5.82E-04 to 7.01E-03 kg SO_2 eq after the operation of the aeration tanks as shown in Figure 9. The AP is expected to increase from 7.65E-04 to 9.22E-03 mole H + eq as shown in Figure 10.

Terrestrial and aquatic eutrophication

Eutrophication is the excess of nutrients caused by air pollution, wastewater, fertilizers, and chemicals entering the aquatic

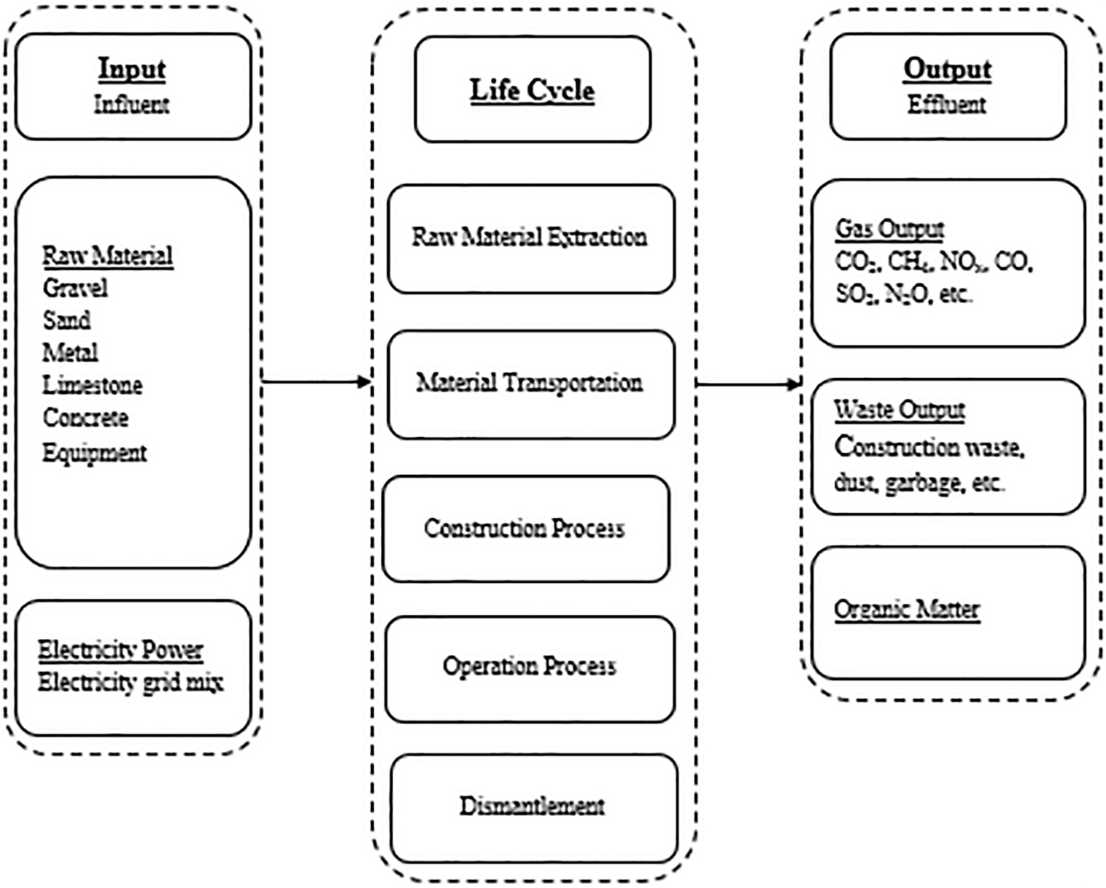

Figure 4. Life cycle assessment flow chart.

Table 6. Units of estimation for the various environmental impact indicators used in this study according to ReCiPe method.[26]

IMPACT FACTOR	REPRESENTATION	UNITS
Global warming potential and climate change	Carbon dioxide equivalents	kg CO_2 eq.
Ozone depletion potential	Chlorofluorocarbon equivalents	kg CFC-11 eq.
Terrestrial acidification	Sulfur dioxide equivalents	kg SO_2 eq.
Acidification potential	Hydrogen cation mole equivalents	Mole of H^+ eq.
Terrestrial eutrophication	Nitrogen mole equivalents	Mole of N eq.
Marine eutrophication	Nitrogen amount equivalents	kg N eq.
Freshwater eutrophication	Phosphorus amount equivalents	kg P eq.
Photochemical ozone formation	Non-Methane Volatile Organic Compounds amount equivalents	kg NMVOC eq.
Human toxicity	1.4-Dichlorbenzol amount equivalents	kg 1.4-DB eq.
Freshwater eco-toxicity	1.4-Dichlorbenzol amount equivalents	kg 1.4-DB eq.
Resources depletion (Mineral + Fossil + Renewable)	Antimony amount equivalents	kg Sb eq.
Fossil depletion	Oil amount equivalents	kg Oil eq.
Metal depletion	Iron amount equivalents	kg Fe eq.
Water depletion	Cubic meters	m^3
Ionizing radiation	uranium isotope amount equivalents	kg U235 eq.
Particulate matter formation	Equivalents to amount of particles that have aerodynamic diameters less than or equal to 10 microns	kg PM10 eq.

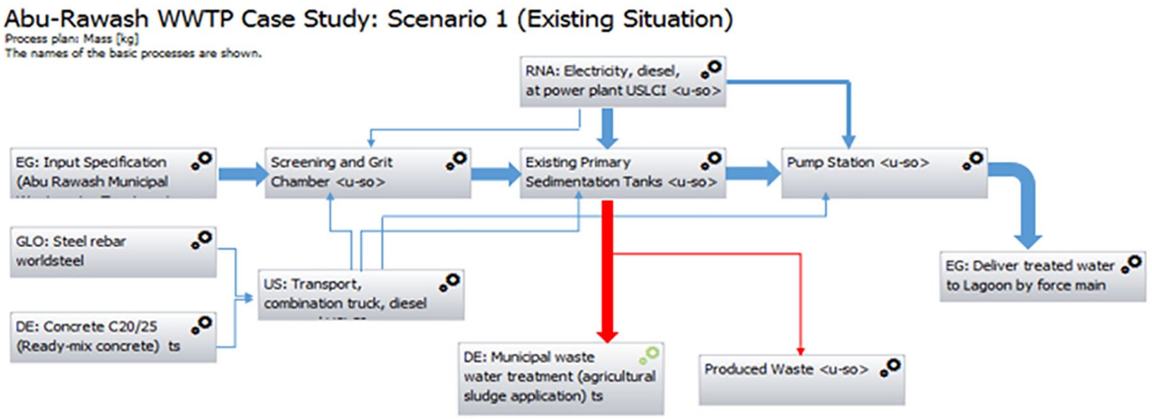

Figure 5. Model building and processes linkage of Scenario 1, as extracted from GaBi. WWTP indicates wastewater treatment plant.

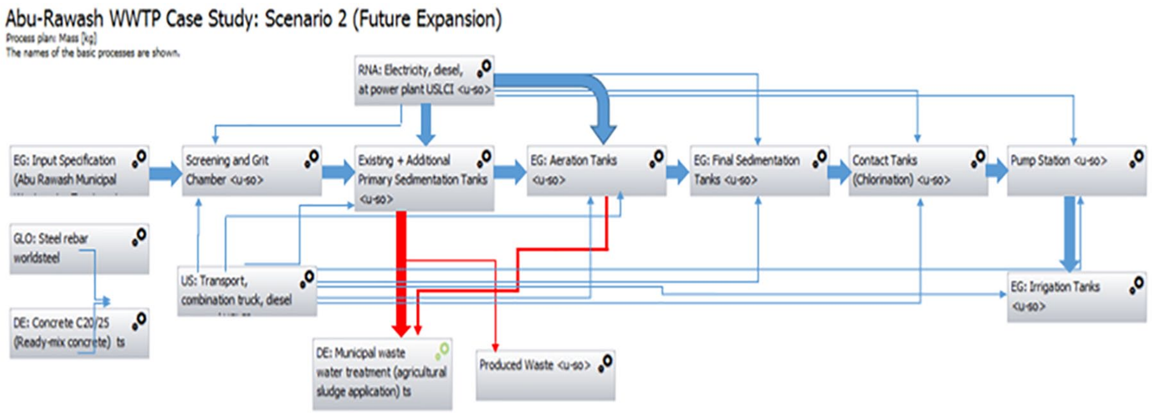

Figure 6. Model building and processes linkage of Scenario 2, as extracted from GaBi. WWTP indicates wastewater treatment plant.

ecosystem. This results in excessive production of aquatic organic matter that becomes a significant water-quality problem.[31] Algal blooms develop and cover the water surface which prevents sunlight from reaching lower depths. In addition, as eutrophication increases the clarity of water decreases, which increases the impedance of sunlight travel. This causes a reduction in the photosynthesis process and, in turn, decreases the production of oxygen, which eventually lead to fish mortality and anaerobic decomposition to take place. Eutrophication results in increased nitrate content in soils and sediments. This, in turn, results in an increase in the nitrate content of the groundwater as water leaches through the affected soil and into the groundwater. The terrestrial and marine eutrophication potentials are estimated in nitrogen equivalents (N eq.) while the freshwater eutrophication potential is estimated in phosphorus equivalents (P eq.).[32]

In Scenario 2 by adding the aeration, final sedimentation and chlorination units, the quality of treatment has increased resulting in producing a higher quality effluent with less N and P equivalents, which are the main cause of eutrophication. The results showed a decrease in the freshwater eutrophication from 2.39E-03 to 1.98E-05 kg P eq as shown in Figure 11. Also, the terrestrial eutrophication is expected to decrease from 2.04E-02 to 1.69E-03 kg N eq as shown in Figure 12, for each 1 m^3 of treated wastewater.

Human toxicity and eco-toxicity

To evaluate the level of human toxicity, Human Toxicity Potential (HTP) assessment is carried out to assess the negative impacts on human. These potential toxicities can be estimated based on 1.4-dichlorbenzol (C6H4Cl2) in the air as a reference substance. On the other hand, to evaluate the eco-toxicity level, eco-toxicity potential assessment is carried out, which evaluates the damages to the aquatic and terrestrial ecosystems. Both properties are estimated 1.4-dichlorbenzol equivalents (1.4 kg DB eq.).[33] The potential toxicity is based on the substance's chemical and physical properties which can be classified into groups such as HTP, Aquatic Eco-Toxicity Potential (AETP), and Terrestrial Eco-toxicity Potential (TETP). It depends on the source of emission and the way it spreads into the atmosphere, water bodies, and soils.

Increasing the quality of treatment in Scenario 2 is expected to produce a higher quality effluent with less nitrogen and phosphorous equivalents. Thus, the results showed an expected decrease in the human toxicity produced from 1.77E-06 to 1.47E-07 kg 1.4-DB eq for cancer as shown in Figure 13 and from 1.46E-05 to 1.21E-06 kg 1.4-DB eq for non-cancer as shown in Figure 14, for each 1 m^3 of treated wastewater.

Increasing the quality of treatment will produce a higher quality effluent with less nitrogen and phosphorous equivalents. Thus, the eco-toxicity results decreased from 8.35E + 01 kg 1.4-DB eq in Scenario 1 to 4.93E + 01 kg 1.4-DB eq in Scenario 2 as shown in Figure 15, for each 1 m^3 of treated wastewater.

Resources depletion

The depletion of natural resources was estimated for the different wall types involved in this study and for various wall height. These natural resources include fossil energy and metals including crude oil, ores, and mineral materials in their raw state as well as non-renewable resources. This impact category takes into consideration the availability of natural elements and the availability of fossil energy. Antimony (Sb) is considered as the reference substance for the characterization factors.[34]

As a result of the huge amount of electricity consumed in the wastewater treatment process, fossil fuel resource depletion is significant. By consuming more energy for the aeration process (future scenario), the abiotic depletion potential (ADP) elements + fossil depletion will increase from 1.79E-06 to 1.49E-05 kg Sb eq as shown in Figure 16. The metal depletion potential has increased from 9.35E + 03 to 3.76E + 04 kg Fe eq for each 1 m^3 of treated wastewater as shown in Figure 17. Extra metal and steel are used to construct the additional units.

Water depletion

Water depletion occurs when water extraction exceeds the renewability rate, which is expressed in cubic meters of freshwater equivalent depleted. This indicator takes into account the loss of water for future generations. It denotes the damage caused by freshwater consumption and can be added to damage caused by other environmental interventions such as emissions, waste, or both.[35]

The results showed a decrease in the water depletion from 7.50E-01 to 4.00E-01 m^3 eq for each 1 m^3 of treated wastewater as shown in Figure 18. Better quality treated sewage effluent (TSE) will be produced and can be utilized in irrigation and other domestic uses. Consequently, this will reduce the pressure on the freshwater resources.

As a result of the comparison between Scenarios 1 and 2, Table 7 summarizes the percentage and the negative as well as the positive impacts of adding secondary treatment units to Abu Rawash WWTP.

Table 7. Percentage and impact of having a secondary treatment units for 1 m^3 of wastewater.

PARAMETER	VALUE	IMPACT
Human toxicity	92% reduction	Positive
Eco-toxicity	41% reduction	Positive
Eutrophication potential	79% reduction	Positive
Terrestrial eutrophication	92% reduction	Positive
Freshwater eutrophication	99% reduction	Positive
Water depletion	47% reduction	Positive
GWP	17% increase	Negative
Ozone depletion potential	99+% increase	Negative
Acidification potential	91% increase	Negative
Terrestrial acidification	91% increase	Negative
Metal depletion	75% increase	Negative
Fossil depletion	20% increase	Negative
ADP elements + fossil	87% increase	Negative

Abbreviations: ADP, abiotic depletion potential; GWP, global warming potential.

Table 8. Cumulative impact of upgrading all WWTPs in Egypt to secondary treatment.

ECO-INDICATOR	UNIT	CUMULATIVE IMPACT
GWP	kg CO_2 eq	147,600
Human toxicity (cancer)	CTUh	1.50
Human toxicity (non-cancer)	CTUh	12.10
Eco toxicity	CTUe	30,780,000
Fossil depletion	kg Oil eq	61,200
Marine eutrophication	kg N eq	16,839
Freshwater eutrophication	kg P eq	2,133
Water depletion	m^3 eq	315,000
Ozone depletion	kg CFC 11 eq	4.81917E-13
ADP elements + fossil	kg Sb eq	1.311E-08
Terrestrial acidification	kg SO_2 eq	0.000000119
Metal depletion	kg Fe eq	28.25
Terrestrial ecosystem	kg 1.4 DB eq	0.00000034

Abbreviations: ADP, abiotic depletion potential; GWP, Global warming potential; WWTP, wastewater treatment plant.

The Influence of This Study on Egypt

About 0.9 billion cubic meters of wastewater in Egypt are currently primary treated.[36] By adding secondary treatment units to all the WWTP that only have primary treatment units, an increase of about 147,000 ton CO_2 eq per year for GWP indicator. A yearly saving in water and fossil depletion is expected to reach 315 million m^3 eq and 61.2 million kg oil eq, respectively. Also, upgrading all WWTPs in Egypt is expected to prevent the release of eco-toxicity by about 30.78 billion CTUe per year. Table 8 shows the cumulative impact of upgrading all WWTPs in Egypt to secondary treatment. The negative consequences from the upgrade process is minor comparing with the positive consequences.

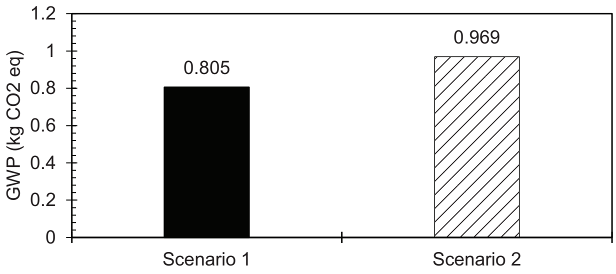

Figure 7. GWP for Scenarios 1 and 2. GWP indicates global warming potential.

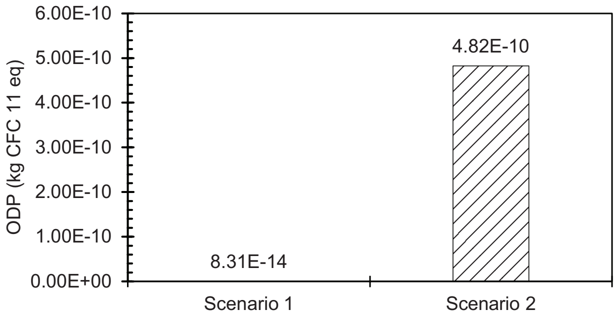

Figure 8. Ozone depletion potential for Scenarios 1 and 2. ODP indicates ozone depletion potential.

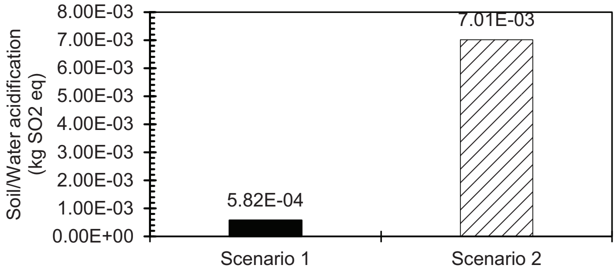

Figure 9. Soil/water acidification for Scenarios 1 and 2.

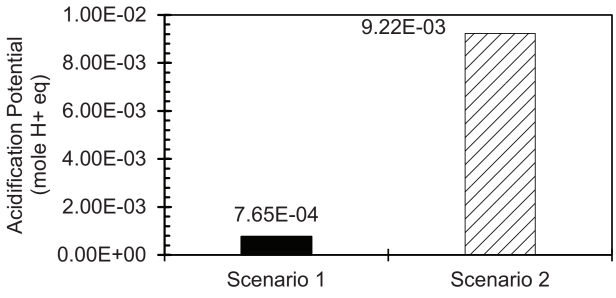

Figure 10. Acidification potential for Scenarios 1 and 2.

Circular Economy, Energy Recovery Approach and Business Model

A circular economy approach was utilized in this study in which energy consumption and production should remain in the economy for as long as possible and recycled to process and re-use. The energy produced from wastewater is in the form of

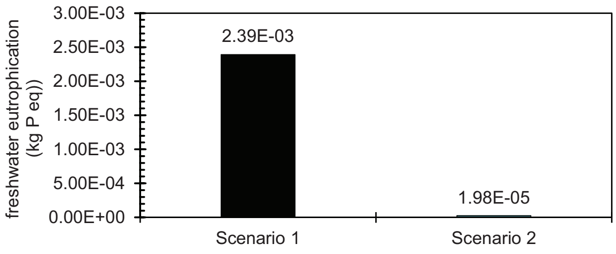

Figure 11. Freshwater eutrophication for Scenarios 1 and 2.

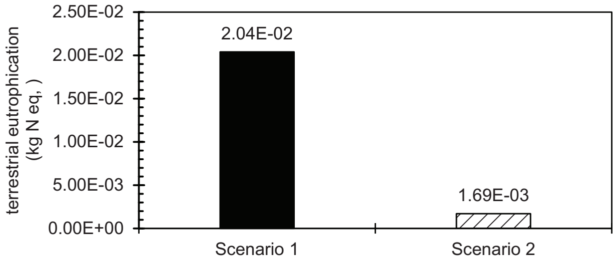

Figure 12. Terrestrial eutrophication for Scenarios 1 and 2.

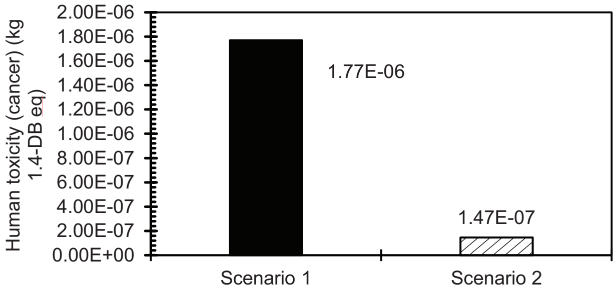

Figure 13. Human toxicity (cancer) for Scenarios 1 and 2.

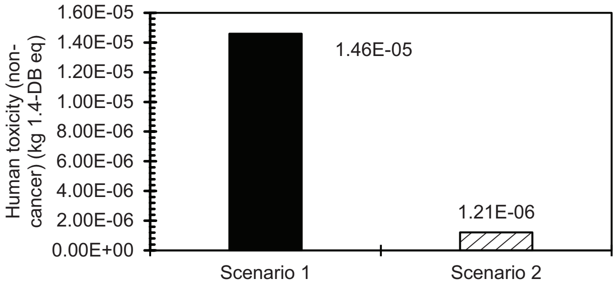

Figure 14. Human toxicity (non-cancer) for Scenarios 1 and 2.

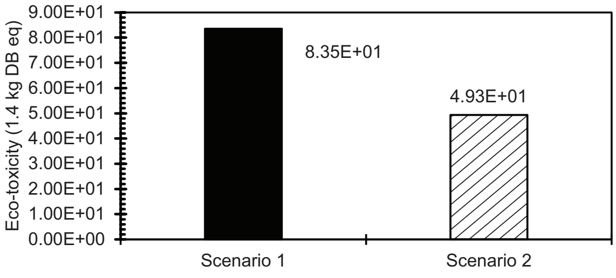

Figure 15. Eco-toxicity for Scenarios 1 and 2.

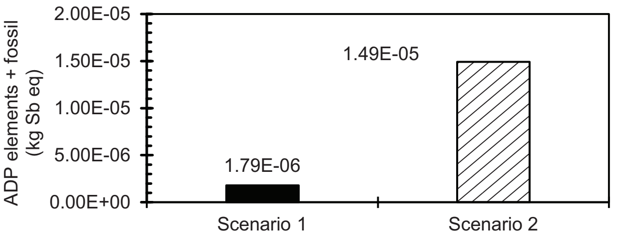

Figure 16. ADP elements + fossil for Scenarios 1 and 2. ADP indicates abiotic depletion potential.

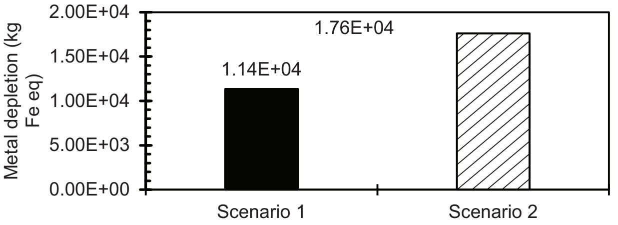

Figure 17. Metal depletion for Scenarios 1 and 2.

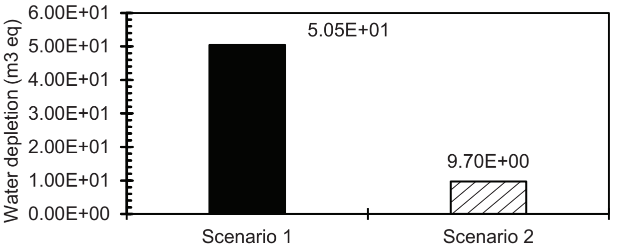

Figure 18. Water depletion for Scenarios 1 and 2.

(1) thermal, (2) hydraulic, and (3) chemical energy. Thermal energy is the heat energy within the wastewater, which can be from hot water users, non-pressurized, or pressurized sewers. In Dalian, a city in the north of China, heat energy was reclaimed from sewage to meet the required heating level for the Xinghai Bay business district, resulting in energy reduction of 30% compared to conventional method.[37] Anaerobic digestion can provide several benefits in WWTPs by producing biogas from wastewater and sludge as renewable and green source of energy. It helps in the reduction of the sludge volumes and disposal costs, in addition to eliminating the pathogens and potential use of dehydrated sludge as a fertilizer. Many WWTPs use anaerobic digestion such as the St. Martin WWTP in Mauritius and the Okhla WWTP in New Delhi, which utilize biogas as a source of energy to meet 25% and 60% of their energy needs, respectively. Also, anaerobic digestion technology is used by agro-industrial units to treat the effluent during production. On the other hand, coupling wastewater treatment with algal biofuel production as well as the incineration of bio-solids in wastewater into heat energy are other methods to produce energy.[38]

The business model typology is mainly based on the value scheme along with the waste value chain and the end use of the generated energy. The business model can be either (1) on-site use or (2) off-site sale. The business model employs either a Build-Own-Operate-Transfer (BOOT) structure or a service provision structure to deliver energy to its end users. The theory of recovering energy from wastewater in Abu Rawash WWTP is based on the following assumptions:

Average water consumption is 200 L/capita/day;

Flow rate of 5 m/s;

At an altitude of 50 m and 40 L/capita/day of greywater generation;

115 g COD/capita/day.

Based on these assumptions and the digester energy production calculations, the potential energy that can be recovered can be estimated as follows:

0.25 kWh/capita/year of kinetic energy;

500 kWh/capita/year of thermal energy;

150 kWh/capita/year of chemical energy.

The investment in recovering energy from WWTP can be significantly efficient and can cut costs by harnessing the energy contained in the wastewater such as energy recovered from sewage flows (2%-10%), from sludge (40%-60%), in addition to improving energy efficiency of the WWTP up to 20% energy savings and generating renewable energy onsite through wind and solar systems (5%-10%). Energy generation in Abu Rawash WWTP will offer great opportunities for earning revenue from trading carbon credit that reduces greenhouse gas (GHG) emissions relative to the business-as-usual scenario. The carbon credits value depends on the GHG emissions savings relative to a business-as-usual scenario and the carbon credits. The price of carbon credit for 1 metric ton of CO_2 is between € 10 and 25 (US$13 to US$33) per ton traded based on the European Climate Exchange.[39]

Upgrade biogas to bio-methane

Biogas is a common element for energy recovery in which biogas can be produced from sewage sludge and sludge through the anaerobic digestion process. Biogas is classified into two types: (1) raw biogas with 60% methane, 30% carbon dioxide, hydrogen sulfide trace component and moisture, while the other type is (2) upgraded biogas with 90% methane. The process of upgrading the biogas to bio-methane comprises the removal of carbon dioxide, hydrogen sulfide and all other possible pollutants from the biogas. The removal of carbon dioxide results in an increase in the methane concentration and an increase in the calorific value of upgraded biogas accordingly. The process of upgrading biogas to bio-methane is increasingly gaining popularity on both economic and environmental sides. In Europe, the main five biogas upgrading technologies which are commercially used are: (1) chemical absorption, (2) pressure water scrubbing, (3) pressure swing adsorption (PSA), (4) cryogenic process, and (5) membrane separation.[40] High pressure water scrubbing and pressure swing absorption are considered to be most feasible due to their low cost, easy maintenance, in addition to their high efficiency.[41]

In Stockholm, the cost of production of biogas from sewage sludge for vehicle use is about 0.22–0.48 € Nm^{-3}.[42] Thus, understanding the financial relation between capital costs and plant capacity is important to identify the optimal plant capacity for Abu Rawash WWTP. Amigun and von Blottnitz,[43] has given an empirical relationship between capital investment and plant capacity

$$\frac{C1}{C2} = \left(\frac{Q1}{Q2}\right)^{n} \tag{1}$$

Where $C1$ is the investment cost at a capacity $Q1$ and $C2$ is the estimated investment cost of a new plant at a capacity $Q2$, n is the cost capacity factor. This can also be written as $C = kQn$. The coefficient n depends on the type of industry. For Abu Rawash WWTP, the digester investment and the O&M costs are 230 $/m^3 and 105 $/year, respectively.

Conclusion

The consideration of the environmental impact of the wastewater treatment plants at different treatment stages became a necessity to understand its impact on the environment and climate change. This paper presented the environmental positive and negative impacts of upgrading Abu-Rawash WWTP in Egypt, as a case study, from primary treatment to secondary treatment WWTP. Secondary treatment units will allow better quality outputs (treated water and clean sludge) have become potential source of irrigation and energy, not waste. The application of the LCA framework in association with GaBi software have proved that LCA is a significant tool to achieve sustainability and assess the environmental impacts of the wastewater treatment plants, and it develops an outstanding approach in the typical wastewater treatment plants.

The study was conducted to investigate the different environmental impacts generated during the extraction, construction, operation, and transportation of materials. It explains the principals and methodology of life cycle assessment. It then provided a numerical score-based tool that evaluate the eco-indicators. It is worth noting that employing the secondary treatment units at Abu Rawash WWTP have both positive and negative impacts. The positive impacts include a reduction in the human toxicity, eco-toxicity, eutrophication potential, terrestrial eutrophication, freshwater eutrophication, and water depletion by 92%, 41%, 79%, 92%, 99%, and 47%, respectively, for each 1 m^3 of treated wastewater. The negative consequences of employing the secondary treatment units for each 1 m^3 of treated wastewater include an increase in GWP, ODP, AP, terrestrial acidification, metal depletion, fossil depletion, and ADP elements + fossil by about 17%, 99%, 91%, 91%, 75%, 20%, and 87%, respectively. The paper extended to study the influence and the cumulative impacts if all the primary treatment WWTPs have been upgraded to secondary ones in Egypt.

It has been found that the electricity required to carry out the wastewater treatment process, has recognizable contribution in all assessment categories. A huge amount of electric energy is consumed in the wastewater treatment and developing alternative sustainable electricity generation from renewable sources for WWTPs became essential to reduce fossil fuel resource depletion and emissions of pollutants. In the light of this, a circular economy concept to reuse energy and a business model were studied to reduce the net amount of energy consumed by proposing approaches to recover energy from WWTP such as upgrading the biogas to bio-methane and reuse the generated energy onsite. This study shall aid the designers to evaluate their candidate solutions. It shall also facilitate avoiding environmental impact overestimation, which may lead to exaggerated environmental protection.

Author Contributions

KMM: Conceptualization, Methodology, Software, Formal analysis, Validation, Investigation, Resources, Writing - Original Draft, Visualization, Project administration.
MKM: Writing - Review & Editing, Resources, Formal analysis.
KZA: Supervision.
MMG: Writing - Review & Editing, Supervision.

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