ECONOMIC AND ENVIRONMENTAL ASSESSMENT OF SEWAGE SLUDGE TREATMENT PROCESSES APPLICATION IN EGYPT

M. R. Ghazy [1], T. Dockhorn [2], and N. Dichtl[3]

[1,2,3] *Institute of Sanitary and Environmental Engineering, Technische Universität Braunschweig, Pockelsstraße 2a, 38106 Braunschweig, Germany, E-mail: m.ghazy@tu-bs.de, t.dochorn@tu-bs.de, n.dichtl@tu-bs.de*

ABSTRACT

The sewage sludge production in Egypt is rapidly increasing resulting from the continuous increase of population, urban planning and industrial developments. This sludge needs to be adequately treated and environmentally managed to reduce the negative impacts of its application or disposal. Therefore, the main currently pressing needs are to find/develop more efficient, economical and sustainable technologies for sludge treatment. The main objectives of this study are to evaluate and compare the application of aerobic/anaerobic digestion, natural/mechanical dewatering and composting processes in sewage sludge treatment options in Egypt with respect to various parameters including energy balance, environmental impacts, sludge capacities and economic aspects. Moreover, the area of application of each treatment process, according to the Egyptian conditions, is evaluated. The Life cycle assessment methodology was applied to assess and compare the environmental impacts of the treatment processes to find out the environmental critical points and to provide a technical and scientific support to the municipal authorities for the environmental optimization of sludge management. The study shows that the application of anaerobic digestion process with energy recovery is proven to be a promising option for sewage sludge stabilization in Egypt. It has the lowest costs and environmental impacts due to the energy recovery. The using of rice straw as a bulking agent in the windrow composting of sewage sludge could help to some extent in reducing the environmental problems arising from the disposal of this agricultural residue. The application of anaerobic digestion process becomes more cost effective for wastewater treatment plants (WWTPs) capacities greater than 40,000 inhabitants (8000 m3/day). Whereas, the drying beds process was more cost effective with WWTPs capacities less than 90,000 inhabitants under Egyptian conditions.

Keyword: Anaerobic digestion, aerobic digestion, windrow composting, environmental impacts, economic aspects, area of application, life cycle assessment.

1. INTRODUCTION

Large ongoing efforts in expanding the sewage sludge treatment processes in Egypt are constantly needed to reduce the serious environmental and public health impacts resulting from the increasing in the wastewater treatment plants without equal attention in dealing with the produced sludge. For many years, less efforts have been given to the produced sludge management and environmental protection in practice. In many cases the produced sludge is applied, disposed or discharged without any adequate treatment. The attention was mainly given to the sludge drying processes, mainly through

natural drying beds, without any interest to the produced sludge quality. Moreover, the implemented methods and technologies for sludge treatment were very limited.

Recently, there is a strong interest for the sewage sludge management due to the accumulation of various serious environmental problems, especially in main cities. Therefore, the current critical needs are to develop more sustainable and low cost methods to treat the produced sludge to be safe and suitable to be reused in agriculture. Furthermore, the current legislations should be adapted to the actual conditions with improvement of the institutional capacity to guarantee their enforcement.

Egypt has currently 303 WWTPS that handle $11.85x10^6$ m^3/day of sewage producing about $2.4x10^3$ tons/day of dry solids with a sludge production rate of 0.225 kg/m^3 of treated wastewater (Ghazy et al. 2009). Due to the continuous rapid growing population, the sewage sludge generation is expected to increase significantly in the future. The current common scenario for sewage sludge treatment and disposal that is applied in most of WWTPs in Egypt can be presented as follow: the primary and secondary sewage sludge are pumped to thickening facilities, mainly gravity thickeners. The thickened sludge is pumped to dewatering facilities mainly natural drying beds to increase its dry solids concentration to 40-60 % DS. After that the dewatered sludge is stored for a period of 1.5 to 6 months before using in agriculture. Recently, there are existing applications of new technologies for sewage sludge treatment that have been successfully implemented in some of WWTPs in Egypt, especially in Cairo and Alexandria governorates. The recent application of anaerobic digestion technology for liquid sludge stabilization and power generation at Al Gabel Asfer WWTP as well as the windrow composting for dried sludge stabilization in Alberka WWTP and 9 N place in Alexandria have achieved good results regarding the produced sludge quality as well as the gained operation and maintenance experiences (Ghazy et al. 2009).

The main issue for selecting a given process or technology lies in deciding which one is the most effective for each project. The economic considerations are the most important parameters that influence the final selection, especially in developing countries (Nobuyuki et al. 2007). Due to the limited available data about the sewage sludge treatment costs in Egypt; the published EPA costs data, a variety of other documents (which have been issued by the U.S. EPA) and other references are used to estimate the missing costs of selected sludge treatment processes (EPA 1985, Gerrard 2001., Murray et al. 2008, Arlt et al. 2002, Zessner et al. 2010). Before using any cost data, it is important to take the local construction market (location factors) and the time value of money (inflation) into account. It is important to know the valid time of any costs data and to adjust the costs according to inflation and location (Murphy et al. 2004). Cost indices are commonly used to update the costs of any treatment process to the present time of estimation (Peter & Bengt 1994). Moreover, the comparison of the current unit costs of operation and maintenance (O&M) requirements in Egyptian as well as international markets are used to adapt the estimated costs to the Egyptian market (location) (Ghazy et al. 2010).

The area of application of sewage sludge treatment processes is different from one country to another and is likely to be significantly different in Egypt due to the big difference in operating conditions and energy prices, which are less than about one fifth of the international prices. The evaluation of the area of application of treatment technologies with respect to the applied location, Egypt, is critical and in great value to the decision makers. The anaerobic digestion process has been generally used for WWTPs having wastewater flow less than 4,000 m^3/day (1 MGD) to more than 757,000 m^3/day (200 MGD). Furthermore, it becomes more cost effective for plants with average flows greater than 8,000 m^3/d (2 MGD). While, the production of electricity from the digested gas recovery becomes more cost effective for plants with daily flows greater than 38,000 m^3/d (10 MGD) (WEF 1992). However, it can be a preferable choice for WWTPs capacities less than 10,000 inhabitants in Germany as referred in many technical discussions (ATV-DVWK 2003). Natural drying beds have been used for more than 100 years. They are commonly used at small WWTPs in warm and sunny regions. In the United

States, a majority of WWTPs with capacities less than 5 MGD use drying beds for sludge dewatering. Similarly, Russia and other Eastern European countries use drying beds in more than 80% of the WWTPs (Turovskiy & Mathai 2006). Conventional sand drying beds are the oldest and most commonly used type of drying beds. It is generally used for communities with populations fewer than 20,000 inhabitants. The limitations of this process are: it requires a large land, needs stabilized sludge to prevent nuisance and odors, is sensitive to climate conditions and requires more labor intensive than mechanical dewatering.

The choice of optimal sewage sludge treatment should be based on the comparison of the total costs (US$/ton), which are necessary to achieve the desired quality and more sustainability (more resource efficient, conserving resources and producing less emissions). Sustainable sludge handling may be defined as a socially acceptable, cost-effective method that meets the requirements of efficient resources recycling while ensuring that harmful substances are not transferred to humans or environment (Lundin et al. 2004). The Life Cycle Assessment (LCA) is one of the most widely known and internationally accepted methodologies to compare the environmental impacts of processes/services and to evaluate their sustainability in the entire life cycle (Amarantos et al. 2007, Lundin et al. 2000). In the life cycle assessment, all resources consumption and pollutant emissions associated with the life cycle of a system or process are considered, such as extraction and processing of raw materials, manufacturing of chemicals, operation, transportation, recycling and final disposal (Lundin et al. 2004). An advantage of LCA is that, the method is very well established and standardized. It also includes an impact assessment phase whereby all the environmental potential impacts are aggregated and quantified. Moreover, several authors employ this methodology to evaluate the environmental burdens of sewage sludge treatment processes (Houillon & Jolliet 2005, Hospido et al. 2005, Hong et al. 2009, Young & Rousseaux 2002, Tjalfe. & Hansen 2003). In this work, the LCA approach was used to evaluate the environmental burdens associated with the use of aerobic/anaerobic digestion, natural/mechanical dewatering and composting processes in sewage sludge treatment options according to Egyptian conditions. This was done by identifying and quantifying the energy and materials used and the waste released to the environment as well as assessing the environmental impacts of those energy and materials.

2. GOAL AND SCOPE OF THE STUDY

The main objectives of this study are to evaluate/compare the application of aerobic/anaerobic digestion, natural/mechanical dewatering and composting processes in sewage sludge treatment options in Egypt with respect to various parameters including energy balance, environmental impacts and economic aspects. The area of application of each process is estimated with respect to the Egyptian conditions. Moreover, the resources consumption, pollutant emissions, and their environmental impacts are evaluated during the operational periods.

3. METHODOLOGY

3.1 Estimation of Economical Costs

During a field study of the main Egyptian WWTPs at the end of 2008, surveys from many sources such as Egyptian Holding Company for Water and Wastewater (HCWW), National Organization for Potable Water & Sanitary Drainage (NOPWSD) and the main WWTPs in Cairo and Alexandria governorates were conducted. The current unit costs of energy, labor hour and land in Egyptian market were evaluated. Data on operation and maintenance (O&M) requirements and costs were collected from the main six wastewater treatment plants in Cairo (AL Gabel Asfer, Helwan, AL Berka, Shobera, Zenin and Abu Rawash). These wastewater treatment plants represent about 37 % of the total wastewater treatment capacity in Egypt.

3.1.1 Investment Costs

The available data of costs of sewage sludge treatment processes in Egypt are very limited and don't allow detailed analysis. The investment costs are estimated using the collected data from various reports as well as

EPA costs data for actual bid documents of sludge treatment processes that have been constructed across the United States (EPA 1985). The EPA models were adapted due to the change in time (inflation) and location. To adapt the time value for the estimated investment costs, the Marshall and Swift Equipment Cost Index (MSECI) was used to adjust the mechanical equipments costs or the combined costs in which equipments are the major components (Chemical Engineering 2009). The remainder costs were adjusted using the Engineering News Record Construction Cost Index (ENRCCI) (ENR 2009).

The investment costs resulting from the EPA based cost models were adapted to the Egyptian conditions (location) based on the current unit costs in Egyptian market. In general, the base investment costs of sludge treatment processes in Egypt can be assumed to be 73 % of the international value as indicated in figure 1 (Ghazy et al. 2010).

3.1.2 Annual O&M Unit Costs

The annual (O&M) requirements for each sludge treatment process include the labor hours, electrical energy, fuel energy as well as the annual materials and maintenance parts. The annual O&M requirements for the selected treatment processes are estimated based on the design dimensions, electrical energy consumption (kWh/ton) and the man-hour labor requirement (hr/ton) calculations. Consequently, the annual O&M costs are estimated based on the actual current unit costs of electricity (US$/kWh) and man-hour (US$/Hr) in Egyptian market. Figure 2 shows the current unit costs of electricity (US$/kWh) and manpower (US$/Hr) required for the O&M in the main WWTPs in Cairo.

EPA based capital cost model				Adapted Egyptian capital cost model			
Mechanical and electrical costs: 30%		Construction costs : 70 %		Mechanical and electrical costs: 34.5%		Construction costs: 38.5%	
M: 70 %	E: 30%	Salaries: 55%	Materials: 45%			Salaries 11.5%	Materials: 27%
100%				73 %			

Source: (Ghazy et al. 2010).

Fig.1 Subdivision of capital costs based on EPA cost model and Egyptian adapted model

According to the Egyptian market prices in 2009, the average unit cost of hourly manpower in the municipal sector is about 0.77 US$/hr. This may seem too low compared to the US market (34 US$/hr). On the other hand, the number of manpower requirements (hr/yr) in Egypt is about 7.5 times higher than in USA. Therefore, the unit cost of O&M man-hour according to Egyptian conditions can be assumed to be 6.0 US$/hr. The unit price of electrical and diesel energy at the Egyptian market are less than one fifth of the international market prices due to government's subsidies. However, there is a general trend in Egypt to lift the subsidies on all goods and services to keep pace with the

international market prices. In this study, the unit cost of electricity is assumed to be 0.02 US$/kWh and the diesel is 0.25 US$/Lit based on the average current energy unit costs in the Egyptian market.

Fig.2 Current unit costs of electrical energy and manpower in Egyptian WWTPs

3.1.3 Cost of Land

The land required for sewage treatment processes is greatly important, especially in locations where land is scarce or expensive. In Egypt, the government often owns the land for most wastewater projects and provides it to the municipal authority free of cost. However, its economical value should be considered when calculating the estimated cost of a project. The cost of land may vary considerably depending on its use, productivity and availability. When land is used for agricultural production, its economical value can be based on its agricultural production capacity (Tsagarakis et al. 2003).

The current prices of agricultural land (Nile valley and Delta) varies between 5 and-15 US$/m^2, where this price may rise to more than 150 US$/m^2 in the areas suitable for residential buildings or close to cities or villages. Despite, the relatively cheap price for the agricultural land in Egypt, it is very difficult to find a large area that is suitable for WWTP projects. This is a direct result from the governmental agriculture policies to maintain the arable areas as well as prevent most farmers from selling their lands. In general, the average unit cost of land can be assumed at 15 US$/m^2 for rural areas (agriculture land) and 35 US$/m^2 at urban areas as well as 5 US$/m^2 at desert area. In this study, the unit cost of land for drying beds and windrow composting processes are assumed at 15 US$/m^2 as a reference value.

3.1.3 Total Annual Equivalent Cost (EAC)

The total equivalent annual cost (EAC) includes the annual operation and maintenance (O&M) expenses as well as the annual fixed investment cost (annual investment costs over project period). The fixed annual capital cost have been calculated by the capital cost recovery factor which is calculated based on the assumptions of an interest rate of 10 % and a depreciation time of 20 years.

3.2 Anaerobic/Aerobic Digestion Costs and Area of Application

Cost effective analysis is carried out to assign which digestion process is more cost efficient with respect to the Egyptian conditions based on WWTPs capacities, total equivalent annual costs (EAC) as well as the following assumptions:

- The solids retention time for the aerobic digestion is 20 days and 17 days for the anaerobic digestion process. The average temperatures of influent sludge is 20 °C and the temperature of operation in aerobic and anaerobic digestions are 20 °C and 35 °C respectively.
- The energy production from the produced biogas was assumed at 32 % electrical and 57 % thermal energy. The heating value of digested gas is 24 MJ/m^3 and the heat loss during the anaerobic digestion process is assumed to be 1260 w/100 m^3.The excess electrical generation is supplied to the main grid and the produced thermal energy is used only for digestion process.
- The daily sludge production is 60 g TDS/capita.

This analysis may differ from one country to another based on many factors such as the availability of operation experience, energy and manpower costs as well as the ambient climate conditions.

3.3 Natural/Mechanical Dewatering Costs and Area of Application

The natural dewatering processes (drying beds) are less complex, easier to operate and require less operational energy than mechanical dewatering systems (Belt filter press). Furthermore, they give good results in Egypt according to the ambient climatic conditions, hot and dry most of the year. However, the need of larger land restricts the economic feasibility in some locations. To evaluate the area of dewatering processes application in Egypt a cost effective analysis is carried out based on the current average land price and operation costs.

The base capital cost of sand drying beds includes the costs of land, one or more front-end loaders, costs of civil works and installation of drain pipes and valves. On the other hand, the operation of BFP dewatering process contains the costs of belt filter press units and building of operation. These costs are estimated for feeding sludge capacities from 5-100 m^3/day with solids concentrations of 4 % according to the Egyptian market prices in 2009 based on the following assumptions.

- The dry solids loading rate of sludge drying bed is 115 kg/m^2·year and the evaporation rate is 16 cm/month and the rate of precipitation in rainiest month is 2 cm/month.
- The press loading rate of BFP dewatering process is 250 kg/m·hr, the daily labor working time is 8 hr/day and the minimum size of BFP is 0.5 m width and two machines minimum.
- The effluent sludge solids concentration is 30 %.

3.4 Windrow Composting Costs and Area of Application

Composting is a cost effective biochemical stabilization method that can prepare the sewage sludge for beneficial use in land applications. The windrow composting is already applied on a limited scale in Egypt and gave good results according to Egyptian conditions. The incoming dewatered sludge is mixed with shredded rice straw (using a weight ratio of 4 parts sludge 30% DS: 1part rice straw 85 % DS: 1 part of old compost 60 % DS) to obtain a mixture with a solids content of 40-50 % and suitable carbon to nitrogen ratio (25:1-35:1). The organic material is left to decompose outdoors with the aid of just watering and mechanical turning for aeration. The composting period of windrow process is assumed 30 days and the maturation period is about 2 months.

The capital cost of windrow composting process includes costs of land, site clearing and grading earthwork, paving of composting area, construction of unloading &mixing structure, operation building and the cost of windrow turning machines. The costs of open windrow composting process, which can be practically applied in Egypt, are calculated based on the EPA cost models and the following assumptions:

- The ratio of recycled old compost in windrow process is 50% and the new bulking agent mixed with dewatered sludge is 0.375 m^3/ton.
- The solids concentration in dewatered sludge and produced compost is 30 % and 65 %, respectively. The volatile solid destroyed during the process is 30 %.

3.5 Life Cycle Impact Assessment (LCIA)

The environmental impact assessments of the aerobic/anaerobic digestion, natural/mechanical dewatering and composting processes were compared using the life cycle assessment (LCA) methodology, which is largely in accordance with the ISO 14040/14044 standards (ISO 14044 2006, ISO 14040 2006). The life cycle inventories of each treatment process include parameters describing energy use, raw materials, emissions to air, emissions to water and waste generation. The flows were normalized to a functional unit (FU) which is defined as the handling of one metric ton of dry thickened solids for the anaerobic and aerobic digestion processes and one metric ton of dry digested solids for the natural/mechanical dewatering and composting processes.

In the Life cycle impact assessment phase, the values of environmental interventions assessed in the inventory analysis phase are interpreted on the basis of their potential contribution to the environmental impacts. The LCIA is typically divided into five phases: selection of impact categories, classification, characterization, normalization, and weighting. In the classification step, the emissions and resources are divided into different groups or impact categories, according to their potential impact on environment. In this study, a set of seven

baseline impact categories as well as the cumulative energy demand were selected as indicated in table 1. Moreover, a well-established midpoint-oriented approach of LCIA methods is used based on the methodological LCA guide which was developed at the center of environmental science of Leiden University (CML) (Guinée et al. 2002). The third step is the characterization step, where all relevant emissions are characterized and quantified by scientifically derived factors (characterization factors) depending on their contribution to the potential environmental damage allowing aggregation into a single score in each impact category.

Table 1 Environmental impact categories and method of assessment

Impact category	Units	LCIA method
Abiotic depletion (ADP)	kg Sb eq	CML 2001*
Acidification (AP)	kg SO_2 eq	"
Eutrophication (EP)	kg PO_4 eq	"
Fresh water aquatic ecotoxicity (FWETP)	kg p-DCB	"
Global warming (GWP)	kg CO_2 eq	"
Human toxicity (HTP)	kg p-DCB	"
photochemical oxidation (POFP)	kg ethylen	"
Terrestrial ecotoxicity (TETP)	kg p-DCB	"
Cumulative energy demand (KEA)	kWh	

.(Guinée et al. 2002, Frischknecht *et al.* 2007a)*Source:

The normalization step is an optional step for LCA that can be applied for a better understanding of the relative importance and magnitude of the characterization results (ISO 14040 2006). The usual approach is to normalize the environmental impacts from characterization step by relating these impacts to the total impact of a given community (Lundin et al. 2004). Due to the limited data on the annual emissions in Egypt, the normalization factors used in this study were selected based on the

situations in the World 1990 as a reference for all impact categories (Frischknecht et al. 2007b). The weighting step was left out in this study since it is generally recognized by its political, ideological and/or ethical values, therefore high degree of subjectivity is always involved.

To model systems or processes and evaluate their environmental impacts, the Umberto software (Umberto 5.5) developed by ***ifu Hamburg***, Germany was used (Ifu 2005). Umberto is a commercial software tool to model, calculate and visualize material as well as energy flow systems. It is used to analyze the process streams along a product life cycle. Results can be assessed using economic and environmental performance indicators. Cost data for materials and processes can be entered to support decision-makers.

3.5.1 System Boundary of Anaerobic/Aerobic Digestion Processes

The systems boundaries of the applied anaerobic/aerobic digestion processes are assigned and the energy and materials mass balances of each process are estimated. The system boundary of the anaerobic digestion process includes the impacts associated with the digestion process itself and the energy recovery in the combined heat power (CHP) units. Furthermore, the avoided impacts associated with the avoided energy (heat/electricity) production required for the process operation as well as the energy recovery. The environmental impacts associated with chemical substances that may be used during the process are not taken into account. Whereas, the energy and materials mass balances of the digestion process are estimated. Whereas, the electrical and heat energy generation from the digestion process is estimated to 746 and 1330 kWh/ton, respectively. From this energy, about 10 % of the electrical energy and 45 % of the thermal energy are used for the process operation. Consequently, the excess electrical energy recovery is estimated at 667 kWh/ton and the excess thermal heat at 735 kWh/ton. The produced electrical energy can be supplied to the main grid and the excess thermal energy is

diffused to the atmosphere due to the warm climate in Egypt and the current limited purposes of thermal energy as shown in figure 3.
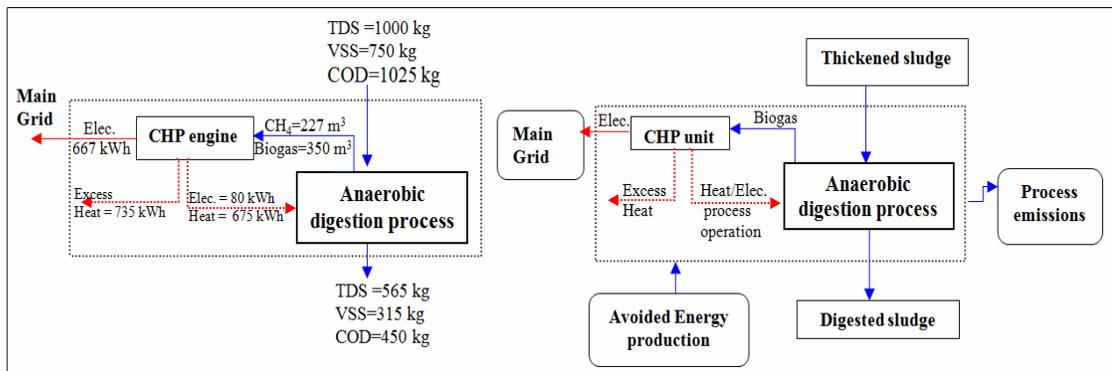

Fig. 3 Systems boundary and material mass balance of anaerobic digestion processes

The system boundary of the applied aerobic digestion process includes the impacts associated with the aerobic digestion process itself and the treatment of the digester supernatant liquid. The scope doesn't include the emissions (e.g. nitrogen oxides) associated with the nitrification/denitrification processes that may be occur during the aerobic digestion process. Whereby, the average required electrical

energy for a continuous operation of aerobic digestion process is estimated to 1176 kWh/ton of digested dry solids and the energy required for the supernatant treatment is estimated at 11 kWh/ton.

3.5.2 System Boundary of Natural/Mechanical Dewatering Processes

The system boundary of the mechanical dewatering facility (BFP) includes the impacts associated with the dewatering process itself (sludge conditioning system, dewatering process, feeding of washing water and recycle of filtrate water). Moreover, it includes the production and transport of required polymer (transport distance of 500 Km) as well as the treatment of filtrated liquor, which has to be treated in the wastewater treatment plant. The system doesn't include neither the impacts of transport of dewatering cake, which will be considered in the next treatment process (composting), nor the disposal (landfill). The electrical demand for BFP process is estimated to 49 kWh/ ton (DS) of dewatered sludge in addition to 40 kWh/ton to treat the filtrated water.

While, the system boundary of the applied drying beds facility includes the impacts associated with the processes of filling beds, mechanical removal of dewatered sludge and periodic replacement of sand as well as the treatment of percolated water. The impacts of evaporation water, expected nitrogen air emissions as well as transport of dewatering sludge are disregarded. The energy required for treating the percolated water resulting from the drying beds is estimated to be 2.17 kWh/ m^3 of percolated water. Whereas the electricity used for the light of site and administration buildings is assumed to be 1 kWh/ ton of dewatered sludge. In addition, the energy needs for mechanical scraping and sand replacement has been estimated at 23 Lit diesel/ton (DS) dry solids.

3.5.3 System Boundary of Windrow Composting Process

The system boundary of the applied composting process as shown in figure 4 encompasses of the impacts associated with the transport of raw resources to the composting plant (rice straw by a distance of 30 km and dewatered sludge by 20 km) and the composting process itself (pre-treatment of bulking agent, formation of windrows, turning/watering and maturation process). It also includes avoided impacts associated with the avoided emissions and saving materials/energy due to fertilizer production as well as the avoided emissions due to the rice straw open burning. The scope of current process excludes the impacts associated with the collection of bulking agent materials (rice straw), the transportation of physical contaminants to landfill, the product testing and bagging as well as excess leachate treatment. The energy and mass balances of the applied composting process is indicated in figure 4. The fuel consumption during the composting process is estimated by 16 lit diesel/ton of dry solids and the electricity demand is estimated by 3.5 kWh/ton.

- *Avoided products and process*

Substitutions are considered for nutrients (NPK) available in the sewage sludge. Thus the environmental effects due to the avoided production of industrial fertilizers (N, P, and K) is considered. This includes the extraction of raw materials and production processes according to German conditions as well as the pre-chain of energy consumption according to Egyptian conditions. The amount of nutrients available in the produced compost is determined based on compost characteristics as indicated in figure 4.

- *Avoided emissions of rice straw open burning*

Egypt is one of the largest rice producer countries in the world (USDA 2002). Where rice cultivation area occupies over 400 x10³ ha with an average farm yield of 8.2 tons/ha and an approximate straw

production of 1.2×10^6 tons/year (3 tons/ha) are disposed, traditionally by burning in situ, causing real environmental problems (Sabaa & Sharaf 1997). This practice produces huge clouds of black smoke that affect most of Delta cities and appear also over Cairo, triggering serious health concerns for more than 20 million residents living in this densely populated city. The use of rice straw as a bulking agent in composting processes will help to some extent in reducing the problems arising from the open burning of this agricultural residue.
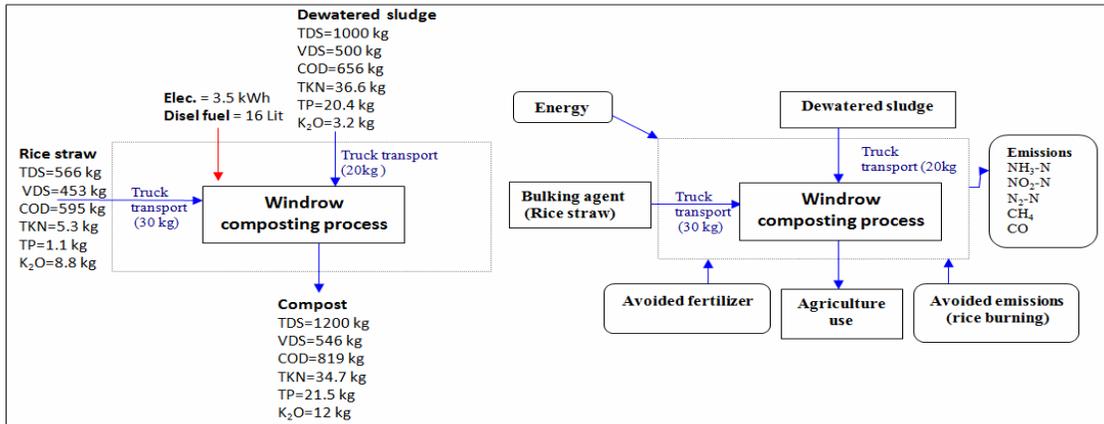

Fig. 4 Systems boundary and material mass balance of windrow composting processes

In this study, the avoided environmental impacts associated with the open burning of agricultural residuals of rice straw is also considered. Open burning of rice straw is a process of uncontrolled combustion during which carbon dioxide (CO_2), the principal product of the combustion, is emitted into the atmosphere along with carbon monoxide (CO), traces of methane (CH_4), nitrogen oxides (NO_x) and comparatively less amount of sulphur dioxide (SO_2). Furthermore, emissions of very harmful air pollutants including polycyclic aromatic hydrocarbons (PAHs) as well as polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) (Gadde et al. 2009). The emissions of CO_2 from fields burning of crop residues are not considered as a net source of CO_2, because the C released to the atmosphere as CO_2 during burning is assumed to be reabsorbed during the next growing season (U.S.EPA 2009).

4. Results and discussion

4.1 Economic Costs

4.1.1 Anaerobic/Aerobic Digestion Costs and Area of Application

The base capital cost of Anaerobic/Aerobic Digestion processes to handle total solid capacities from 1 to 30 tons/day are estimated to 122×10^3 to 933×10^3 US$/ton dry solids digested per day with average value of 169×10^3 US$/ton. While it is estimated at 160×10^3 to 472×10^3 US$/ton for the aerobic digestion with average value of 222×10^3 US$/ton. Figure 5 indicates the results of the cost effective analysis of Anaerobic/Aerobic digestion application according to the Egyptian conditions. The use of anaerobic digestion process will be less expensive for WWTPs with capacities greater than 37,000 inhabitants considering the effect of energy recovery from the produced biogas. Referring only to the effect of the base capital costs without considering the annual operating and maintenance costs as well as the energy recovery from the produced biogas, the aerobic digestion process is to be more

expensive for WWTPs with served population less than 75,000 inhabitants, where it becomes less expensive after that.
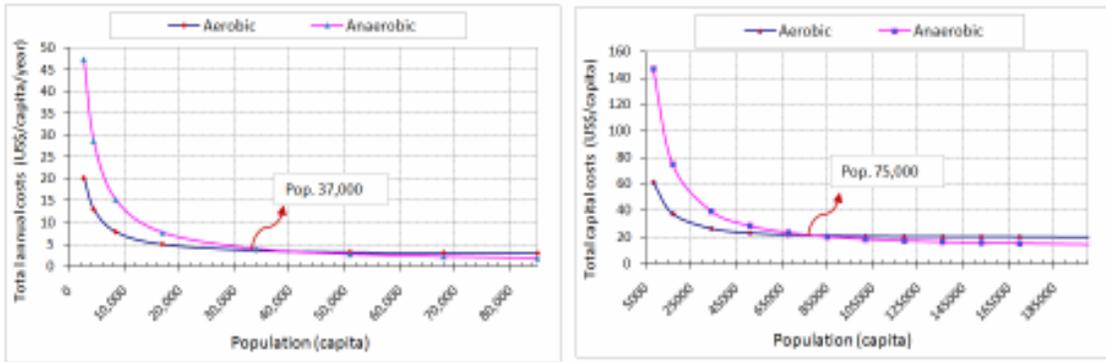

Fig. 5 Area of anaerobic/aerobic digestion application in Egypt

Due to the current low price of energy in the Egyptian market, the area of application of anaerobic digestion technology seemed to be smaller than those in the world. But it should be noted that, the price of energy in Egyptian market is continuously increasing due to the general trend of government to lift the subsidies at the energy sector (to be in line with the global market prices). Consequently, the area of anaerobic digestion application in Egypt can be extending to 20,000 inhabitants considering the global price of energy. In spite of this perspective and as a result of current limited experience of anaerobic digestion operation and lack of control and monitoring for the WWTPs operation in Egypt, especially in small plants, it is recommended to use the anaerobic digestion for WWTPs capacities of more than 40,000 inhabitants (8,000 m^3/day in rural area and 10,000 m^3/day in urban) with preparing qualified staff for operation.

4.1.2 Natural/Mechanical Dewatering Costs and Area of Application

The base capital cost of drying beds process to handle daily sludge capacities from 1 to 100 m^3/day is estimated by 22,000 to 10,000 to US\$/m^3·day with average value of 11,000 US\$/m^3.
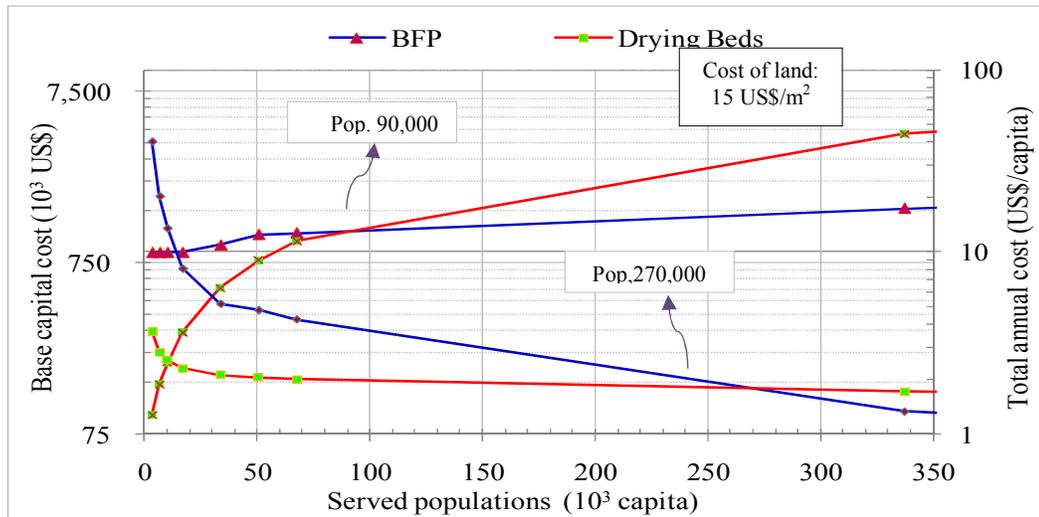

Fig. 6 Area of Mechanical/Natural dewatering application in rural area in Egypt

While it is estimated at 214,000 to 15,000 US$/m³·day with average value of 30,000 US$/m³ for BFP dewatering process. Figure 6 shows the result of the cost effective analysis which is carried out based on the current average land price (15 US$/m²). Considering only the effect of capital cost, the mechanical dewatering process was more cost effective for WWTPs capacities greater than 90,000 inhabitants. While the natural dewatering process was more cost effective with WWTPs capacities of 27, 0000 inhabitants regarding the total annual equivalent costs. It can also be a preferable choice with bigger capacities in desert area (4 US$/m²).

4.1.3 Windrow Composting Costs and Area of Application

The base capital costs and required site area for windrow composting process to handle total solids capacities from 1 to 65 tons/day are estimated according to Egyptian market prices in 2009 as shown in figures 7. The base capital costs are estimated to be 7.9×10^5 to 74×10^3 US$/ton dry solids composted per day with average value of 98×10^3 US$/ton assuming the unit cost of land is 15 US$/m².
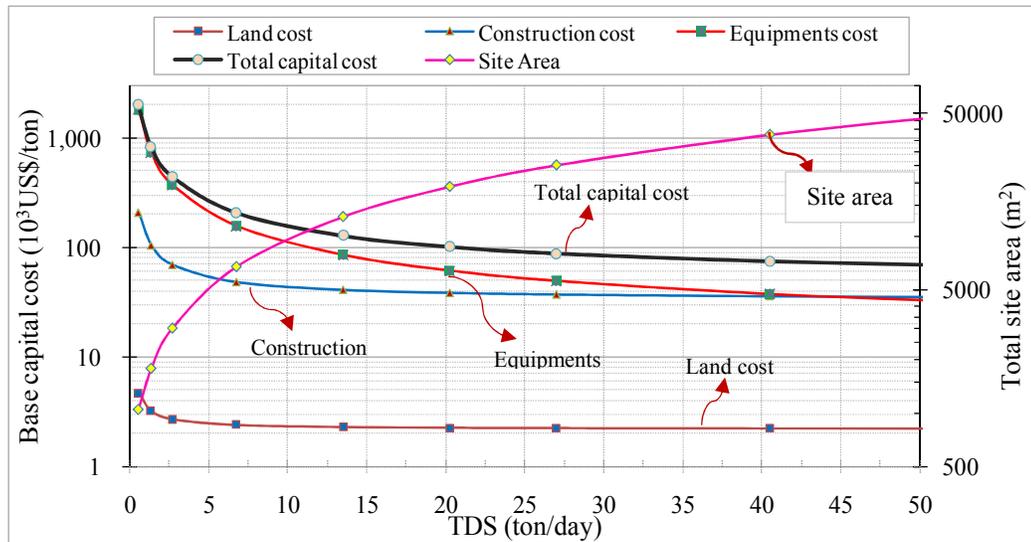

Fig .7 Base capital cost/required area of windrow composting process

4.2 Environmental Assessment

4.2.1 Environmental Impacts of Anaerobic/Aerobic Digestion Process

Figure 8 shows the contribution of each digestion process to the tested environmental impact categories irrespective of the environmental enhance due to avoided emissions resulting from the energy recovery. The potential environmental impacts of aerobic digestion process were significantly higher in all categories under the study. For example, the global warming potential of the aerobic digestion application was 1000 kg CO_2 eq/ton of dry digested solids. While it was only 64 kg CO_2 eq/ton for the anaerobic digestion without considering the effect of excess energy recovery. This is mainly due to the increase in energy consumption for aerobic digestion process. The total cumulative energy demand (KEA) accounts to 3565 kWh/ton of dry digested solids in aerobic digestion process, while the anaerobic digestion process produces a cumulative electrical energy of 1694 kWh/ton. The

cumulative energy (primary energy) is the energy embodied in natural resources (e.g. coal, crude oil, natural gas, uranium) which has not undergone any anthropogenic conversion or transformation. Thereby, it has a mutual influence on efficiency of using natural resources in the overall system or process (Amarantos et al. 2007).
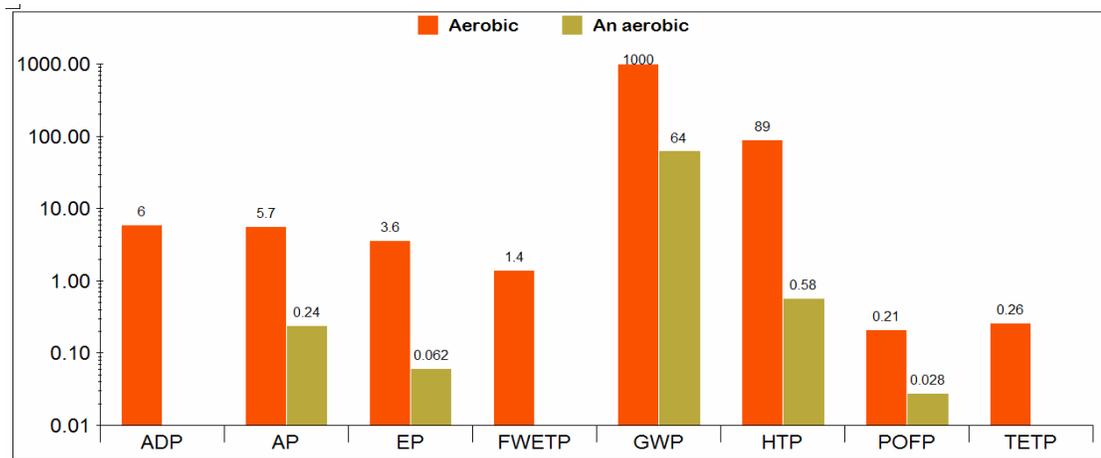

Fig. 8 Environmental impact categories of anaerobic/aerobic digestion process in Egypt

Table 2. Impact categories considering avoided emissions due to energy recovery

Item	Aerobic digestion	Anaerobic digestion	Unit
Abiotic depletion (ADP)	5.97	-2.83[*]	kg Sb eq
Acidification (AP)	5.72	-2.72	kg SO_2 eq
Eutrophication (EP)	3.62	-0.12	kg PO_4 eq
FW aq. ecotoxicity (FWETP)	1.39	-0.66	kg p-DCB
Global warming (GWP)	1010	-480	kg CO_2 eq
Human toxicity (HTP)	89	-42	kg p-DCB
Photochemical oxidation (POFP)	0.21	-0.10	kg ethylen
Terrestrial ecotoxicity (TETP)	0.26	-0.12	kg p-DCB
Cumulative energy demand (KEA)	3565	-1694	kWh

[*] The negative sign means a positive enhancement to environmental categories

Considering the effect of avoided emissions resulting from the avoided electric energy generation, the anaerobic digestion process showed a positive enhancement in all environmental impact categories as indicated in table 2. This benefit is particularly significant in acidification, climate change and depletion of abiotic resources categories, due to energy saving credit. While the application of aerobic digestion process increased the potential contribution of global warming, acidification and abiotic resources depletion to 1010 kg CO_2 eq, 5.72 kg SO_2 eq and 5.97 kg Sb eq/ton dry digested solids, the anaerobic digestion process reduced the potential impacts of these categories to -480 kg CO_2 eq, -2.72 kg SO_2 eq and -2.83 kg Sb eq /ton respectively.

4.2.2 Environmental Impacts of Natural/Mechanical Dewatering Process

The environmental impacts of the drying beds and BFP dewatering processes are shown in figure 9. The potential environmental impacts from the BFP dewatering process were significantly higher in the

toxicological stress on human health and ecosystems (FWETP, HTP and TETP impact categories). The main reason for this is due to the emissions emitted to the environment during the transfer process of dewatered cake which are representing more than 90 % of the total toxicological impacts of the BFP process (274 kg p-DCB). Whereas, the potential environmental impacts from the drying beds dewatering process were slightly higher in the abiotic depletion impact category irrespective of land use, acidification, global warming and the cumulative energy demand. This could be mainly due to the emissions resulting from the machinery work which are responsible for more than 65 % of the potential environmental impacts of ADP, AP and GWP impact categories as well as the cumulative energy demand for the natural dewatering process.
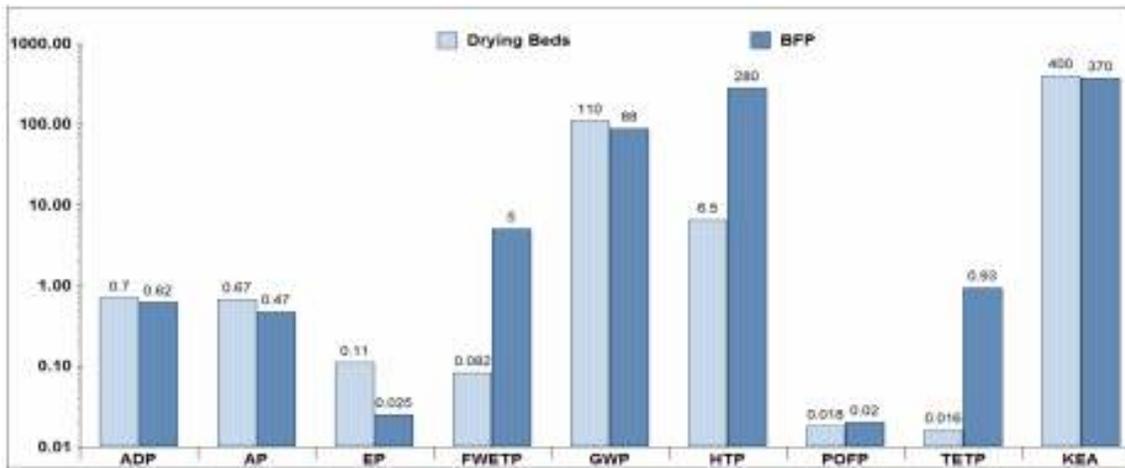

Fig. 9 Environmental impact categories of natural/mechanical dewatering process

4.2.3 Environmental Impacts of Windrow Composting Process

Table 3. Environmental impact categories of the windrow composting process

Item	Without avoided emissions	With avoided emissions	Unit
Abiotic depletion (ADP)	0.50	-2.14[*]	kg Sb eq
Acidification (AP)	11.42	5.40	kg SO_2 eq
Eutrophication (EP)	2.55	2.03	kg PO_4 eq
FW aq. ecotoxicity (FWETP)	5.39	4.77	kg p-DCB
Global warming (GWP)	326	-446[*]	kg CO_2 eq
Human toxicity (HTP)	302.5	257	kg p-DCB
Photochemical oxidation (POFP)	0.08	-0.62[*]	kg ethylen
Terrestrial ecotoxicity (TETP)	0.99	0.88	kg p-DCB
Cumulative energy demand (KEA)	280	-1299[+]	kWh

* The negative sign means a positive enhancement to environmental categories
*The negative sign means energy saving

Table 3 indicates the environmental impacts of the sewage sludge windrow composting using rice straw as a bulking agent. Considering the avoided emissions resulting from the avoided of rice straw open burning and industrial fertilizer production, the windrow composting process has a significant positive effect in most of the environmental impact categories. The results showed a positive enhancement to the global warming by 446 kg CO2 eq, the depletion of abiotic resources by 2.14 kg

Sb eq and the photochemical oxidation by 0.62 kg ethylen as well as a significant reduction in the other environmental impact categories. The use of produced compost as an organic fertilizer is saving about 1299 kWh/F·U of the cumulative energy demand for industrial fertilizer production.

5. CONCLUSION

Although the average income (GDP) in Egypt is 95 % lower than the average income in the USA (in 2009), the capital costs of sewage sludge treatment are only 27 % less in Egypt than in the USA. The main difference in the total costs of sludge treatment processes in Egypt compared with the international market can be explained by the significant difference in the annual O&M costs resulting from the low hourly manpower and energy prices. This difference can be rapidly changed in the future as a result of government tendency to follow the policies of globalization and the free market trade. The current average unit price of man-hour in the municipal sector is 90 % less in Egypt than that in the USA, while the number of required man-hour is about 7.5 times higher in Egypt than the USA. The current unit cost of electrical energy in Egyptian market is less than one fifth of costs in the US market due to governmental support of energy sector in Egypt.

The average required cumulative energy demand (KEA) for a continuous operation of aerobic digestion process is estimated at 3565 kWh/ton of digested dry solids while the final cumulative electrical energy production from the anaerobic digestion process is estimated at 1694 kWh/ton. This energy can be supplied to the main grid, while the excess thermal energy is diffused to atmosphere due to the warm climate and limited thermal energy application purposes in Egypt. Moreover, the cumulative energy demand of the drying beds and BFP dewatering processes are estimated at 400 and 370 kWh/ton of dewatered dry solids respectively. On the other hand, the using of windrow composting process can save a cumulative energy consumption of 1299 kWh/ton due to the avoided industrial fertilizer production.

The application of anaerobic digestion technology in Egypt is more cost effective for WWTPs with capacities greater than 40,000 inhabitants, while it can be the best choice for other countries at generally much less capacity. This is mainly due to the current low energy prices in Egyptian market. The drying beds process was more cost effective with WWTPs capacities greater than 270,000 inhabitants regarding the total annual equivalent costs. While the mechanical dewatering process was more cost effective with WWTPs capacities greater than 90,000 inhabitants considering only the effect of capital cost.

The environmental assessment of sewage sludge treatment processes indicated that the application of aerobic digestion for sewage sludge stabilization in Egypt showed higher negative impacts for all environmental categories in this study, while the application of anaerobic digestion showed a positive enhancement in all environmental categories considering the effect of avoided emissions resulting from the avoided electric energy generation. The application of windrow composting process using the rice straw as a bulking agent has a positive effect on the global warming potential, the depletion of abiotic resources and the photochemical oxidation. Also, the utilization of produced compost as an organic fertilizer is saving about 1299 kWh/F·U of the cumulative energy demand for the industrial fertilizer production. The environmental impacts of the BFP dewatering process were significantly higher in the toxicological risk on human health and ecosystems.While the potential environmental impacts from the drying beds dewatering process were slightly higher in the abiotic depletion impact category, acidification, global warming and the cumulative energy demand.

As a general conclusion, the application of anaerobic digestion process with energy recovery is shown to be a promising option for sewage sludge stabilization in Egypt. It leads to the lowest economic costs

and environmental impacts due to energy recovery. The biogas production has a mitigation effect on environmental

impacts due to fossil fuel substitution as well as economic benefit due to the electrical generation. Furthermore, the using of rice straw as a bulking agent in the windrow composting of sewage sludge could help, to some extent, in reducing the environmental problems arising from the open burning of this agricultural residue in Egypt. The use of drying beds process in sludge dewatering could be restricted to the availability and cost of land as well as the capacity of WWTP. Moreover, it has in general negative environmental effects higher than the mechanical dewatering process.

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