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Toward achieving sustainable management of municipal wastewater sludge in Egypt: The current status and future prospective

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A R T I C L E I N F O

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A B S T R A C T

Over the past 4 decades, the increasing amounts of excess sludge from municipal wastewater treatment plants (WWTPs) represent a challenge toward achieving the sustainability of the drinking water and sanitation sector in Egypt, resulting in a serious environmental pollution due to the uncontrolled use of non-stabilized sludge. Here, we report a comprehensive overview on the current situation of excess sludge production, management, and disposal in Egypt. Owing to the technologies used for wastewater treatment in Egypt that mainly consist of activated sludge based-technologies, about 2.1 million tons of dry solids is produced annually. The majority of WWTPs in Egypt lack proper sludge stabilization facilities, except for the WWTPs in high living standards governorates (e.g., Cairo, Alexandria, and Giza). Therefore, about 85% of the non-stabilized sludge is improperly disposed and directly used for agricultural purposes. Despite the importance of managing the use of non- and/or partially-treated sludge, especially for agricultural purposes, the national legislations for sludge disposal/reuse in Egypt are incomplete and, in practice, they are not reinforced. In order to evaluate the most sustainable scenario for sludge management in Egypt, a qualitative decision-support system (DSS) was used. The DSS framework was refined and estimated, based on several evaluating categories, and used to guide the decision process towards achieving sustainable management of municipal wastewater sludge in Egypt. The results reveals that "sludge-to-energy" through anaerobic digestion is the most sustainable scenario for sludge disposal and management in Egypt. The anaerobic digestion-based technology seems to offer advantages of interest at affordable costs, such as the production of renewable energy, stabilized soil conditioners, and fertilizers for agricultural purposes.

1. Introduction

Municipal wastewater sludge is an inevitable by-product from biological wastewater treatment processes, which usually requires high costs for proper handling, disposal, and treatment – often accounting for ~30–40% of the capital cost and ~50% of the operating costs of the entire wastewater treatment plants (WWTPs) [1,2]. Sludge consists of a myriad of contaminates, including organic compounds, nutrients, and pathogens, which creates odors and hygiene concerns [3–5]. Because sludge represents one of the major environmental problems, appropriate treatment and careful management strategies are required [6–8]. The quantity and quality of sludge are significantly impacted by several factors, such as type of wastewater treatment technology used, treatment efficiency, and incoming wastewater volume and composition [9,10]. The sludge treatment and stabilization techniques prior to disposal generally consist of moisture reductions and stabilizing organic matter by digesting, composting, or heat treatment [11].

Converting sludge into value-added products, such as renewable energy, could substantially lower the costs of wastewater (WW) treatment and the consumption of fossil energy, which, in turn would lower greenhouse gas emissions at WWTPs [12–15]. Nonetheless, sludge management is still one of the major environmental, regulatory, and financial challenges facing the sanitation sector and WWTPs owners in specific. For example, owing to the strict legalizations in most industrialized countries, excess sludge requires extensive treatment before it can be used as a valuable fertilizer for land reclamation. The current methods for sludge handling include sludge thickening and dewatering, drying, and stabilization with different chemical, physical, and biological technologies [15–20]. If the agricultural use of stabilized excess sludge is not allowed, it is deposited in sanitary landfills, which is one of the most commonly-used routes in the European Union or directed to

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Nomenclature

AD	Anaerobic digestion
BCM	Billion cubic meters
CHP	Combined heat and power
DS	Dry solids
DSS	Decision support systems
GHG	Greenhouse gases
GOPW	General Organization for Potable Water
GOSSD	General Organization of Sewerage and Sanitary Drainage
HCWW	Holding Company for Water and Wastewater
HRT	Hydraulic retention time
MCM	Million cubic meter
MHPU	Ministry of Housing and Public Utilities
MWRI	Ministry of Water Resources & Irrigation
MWSU	Ministry of Water and Sanitation Utilities
NOPWASD	National Organization for Potable Water and Sanitary Drainage
O&M	Operation and maintenance
OM	Organic matter
PPP	Public–private partnership (PPP)
scf	Standard cubic foot
SRT	Solids retention time
WW	Wastewater
WWTPs	Wastewater treatment plants

incineration plants in order to prevent the accumulation of any undesirable contaminates (e.g., pathogens, heavy metals, and organic contaminates) in the food chain [16,17].

On the other hand, the current situation regarding sludge management and disposal in developing countries is more severe. Owing to the financial constraints and limited reinforcement of environmental laws, developing countries often lack adequate capability for handling the municipal wastewater sludge, resulting in serious environmental pollution [21,22]. For instance, in Egypt, the mere focus is on municipal wastewater treatment instead of sludge disposal and management. Consequently, the disposal of municipal wastewater sludge remains a challenging task in Egypt. Thus, there is an urgent need to develop realistic scenarios that are capable of finding sustainable municipal wastewater sludge management [23,24]. To the best of our knowledge, there is no clear overview of sludge management in Egypt. Therefore, there is an urgent need to assess the current situation of sludge production, management, and disposal in Egypt to get a comprehensive insight into resolving this problem. The overarching goal of this study is to prepare a comprehensive overview of the current situation of sludge production, management, and disposal in Egypt. Second, the current challenges and future opportunities for economic and sustainable reuse of municipal wastewater sludge in Egypt were discussed. Third, a systematic decision support framework – that can be used to guide the decision-making and deployment processes towards achieving sustainable management and disposal of municipal wastewater sludge in Egypt – was developed and evaluated.

2. Material and methods

2.1. Data collection

In order to achieve the study goals, a number of field studies and surveys were conducted based on a semi-structured questionnaire with stakeholders (i.e., scientific experts, local municipalities, WWTPs managers and operators, and non-governmental organizations (NGOs)) in 5 Egyptian governorates: Cairo, Giza, Alexandria, Sharqia, and Kafr El-Sheikh – that generate ~ 75% of sludge produced in Egypt at the beginning of 2018 over a six-month period. The questionnaire was designed to fit the study goals by evaluating the performance of wastewater treatment processes, especially sludge treatment and handling. The main strategy for information and data procurement were: (1) analysis of the official documents related to WWTPs and sewage sludge management (e.g., the impact of wastewater treatment and sludge handing on the environment, institutional framework, socio-cultural acceptance, future plans for enchantment); (2) identification of potential stakeholder, especially from private sectors; (3) organization of semi-structured interviews with the officials and practitioners from WWTPs; (4) review of local legislation and regulations for sewage sludge disposal and management; and (5) direct measurement and observations. During our field studies, information on wastewater treatment and sludge disposal, such as the capacity of WWTP (in m^3/day), the operating condition of WWTP (i.e., hydraulic retention time, systems volume, sludge age, recirculation ratio … etc.), the efficiency of WWTP, sludge production (in dry matter tonnes), the disposal technology used, the operation and maintenance (O&M) requirements and costs, future plans for sludge disposal, and the driving forces for establishing municipal wastewater sludge stabilization facilities, were collected. Stakeholders were classified according to their interests and power degrees during decision-making processes (e.g., "low" for scientific experts, "medium-high" NGOs, and "high" for WWTPs municipalities & managers). They contributed to the survey by providing essential information to accomplish the decision support systems analysis as well as their perception on the best technology/route for sludge disposal in Egypt (based on economic, socio-cultural, environmental, and technological criteria).

2.2. Sludge sampling and analysis

Due to the limited available information on sludge characteristics, municipal wastewater sludge samples (n = 56) were collected during the field surveys. Following samples procurement, samples were kept refrigerated (at 4 °C), and immediately transported to the Central Laboratory of the Holding Company for Water and Wastewater (HCWW) for analyses. Samples were characterized for pH, electrical conductivity (EC), total and volatile solids, organic matter, total nitrogen, phosphorous, and pathogens according to the standard methods for the examination of water and wastewater [25]. Heavy metals content was analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-OES) after acid pre-treatment.

Experimental results were analyzed the SPSS statistics for Windows (version 24, IBM Corp). Data was presented as averages and standard deviations (SD) (average ± SD). All results were considered statistically significant at the 5% level.

2.3. Decision support systems analysis

In this study, a computer-based methodology, known as decision support systems (DSS) was used to evaluate the possible scenarios for sustainable sludge disposal and management in Egypt. The DSS offers a systematic framework for the analysis of a specific decision issue, which, in turn, will ensure an equitable, accurate assessment of the decision process through a well-established procedure. Here, the methodology described in Bertanza et al. [26] was adopted using 4 evaluation categories (i.e., economic aspects, socio-cultural aspects, environmental aspects, and technological aspects) (Table 1). Briefly, the evaluation attributes were ranked according to their problematic values (e.g., green color means that the attribute has a positive/beneficial impact; red color means that the attribute has a critical situation; and yellow represents an

Table 1
Evaluation categories and attributes used in the DSS framework analysis.

Category	Attributes	Evaluation criteria[a]		
		Beneficial (positive) impact (green)	Neutral impact (Yellow)	Negative impact (Red)
Economic aspects	Investment cost	Low	Medium	High
	O & M cost	Low	Medium	High
	Profit	High	Medium	Low
Socio-cultural aspects	Social acceptance	High	Medium	Low
	Heavy metals-associated risks	Low	Medium	High
	Pathogen-associated risk	Low	Medium	High
	Emissions	Low	Medium	High
Environmental aspects	Recovered value-added products	High	Medium	Negligible
	Solids residues to be disposed	Negligible	Medium	High
	Land requirement	Low	Medium	High
	Transportation distance	Short	Medium	Long
	Odors	Negligible	Little significant	High significant
	Noise	Negligible	Little significant	High significant
	Heavy metal emission risk	Low	Medium	High
	Pathogen emission risk	Low	Medium	High
	Air emission risk	Low	Medium	High
Technological aspects	Reliability	High	Medium	Low
	Flexibility and modularity	High	Medium	Low
	Complexity	Low	Medium	High
	Personal requirements[b]	<10%	10–20	>20%
	Reagents consumption[b]	<10%	10–50	>50%
	Energy consumption[b]	<10%	10–50	>50%

[a] Evaluation criteria were adapted from Ref. [26].
[b] Values are presented compared to the current situation.

intermediate case). Following the attributes ranking, they were given numerical values: “1” for green, “− 1” for red, and “0” for yellow. Finally, the sludge management scenario was calculated based on the numerical value of its attributes according to the following scale: “> 0.33” for green, “− 0.33 to 0.33” for yellow, and “< − 0.33” for red. The possible scenarios for sustainable sludge disposal and management considered in this study were: (1) anaerobic digestion, (2) aerobic composting, (3) use in agriculture, (4) anaerobic co-digestion, and (5) disposal in engineering landfill. Incineration and other thermal stabilization approaches were discarded in this study due to the lack of these technologies implementation in Egypt. The DSS model was implemented using Microsoft Excel® 2016 spreadsheet as described elsewhere [26].

3. Results and discussion

3.1. Sludge production in Egypt

Over the past 4 decades, the Egyptian government has faced tremendous challenges to provide safe drinking water and sanitation services. It has been reported that the Egyptian government has invested about 30 billion US $ to improve the water and wastewater infrastructure and services, with the majority of these investments being focused on drinking water supply and sanitation-related services, especially constructing new sewerage networks and wastewater treatment facilities [27,28]. However, the majority of Egyptian investments have been primarily focused on providing large centralized sanitation-related services and infrastructure with little attention given to sludge disposal and management [24,29]. Given that the capital cost as well as operation and maintenance (O&M) cost of wastewater treatment facilities are high, it became clear that it is not possible to recover the full costs of treatment from the end users, making wastewater treatment facilities financially not sustainable. Owing to the recent advances in conservation and infrastructure improvement, Egypt has achieved slight improvement in sanitation coverage with nearly 57% of the population have access to the sanitary networks, especially in the urban areas (Table 2) [30].

Within the 27 Egyptian governorates, there are 415 wastewater treatment plants (WWTPs) that handle ~ 4.4 billion cubic meters (BCM) of municipal wastewater annually, which is expected to reach 8.8 BCM by 2030 [31]. 66% of WWTPs in Egypt are centralized activated sludge-based treatment systems (Fig. 1A) [30]. WWTPs in Egypt are divided into 8 categories, based on wastewater treatment capacity, with ~ 85% of WWTPs have small to medium WW capacity (i.e., 50,000 m^3 per day) (Fig. 1B). Approximately 2.1 million tonne of excess sludge is produced annually, with an average sludge production of 0.48 kg sludge per 1 m^3 of treated wastewater. The average per capita sludge production is nearly 17.1 kg dry solids (DS) in 2018, which is comparable with values reported for more developed countries [17]. Fig. 2A shows sludge production and per capita sludge production of each governorate in Egypt. It is obvious that sludge was generated in higher quantity in the Northern part of Egypt (Fig. 2B), which is most likely due to the higher sanitation coverage and wastewater treatment capacity, industrialization, standard of living, and population density, although there was no difference in the implemented wastewater treatment technologies. The majority of sludge production (i.e., ~70%) and per capita sludge production is generated from only 3 governorates (Cairo, Giza, and Alexandria), with a little amount generated in the Southern part, mainly due to the limited number of installed WWTPs, of which most consist of waste stabilization ponds. In addition, the amount of sludge produced is expected to be doubled in the coming few years due to population increase and the construction of new WWTPs [23].

Due to financial constraints and limited areas available for extensive sludge treatment in the majority of WWTPs, especially in the Nile Delta, there are no sludge stabilization facilities, and the sludge that has been dried in plain sludge drying beds is sold directly to local vendors with an average gate price of ~ 4–6 US$ per 1 tonne. However, the vendors are obliged to store the sludge for up to 6 months prior to use in land application according to the national legislations for sludge disposal/reuse that prevent the use of non-stabilized sludge in edible vegetables and fruits. In practice, however, these regulations are not reinforced, and commonly, excess primary and secondary sludge are sold to farmers without any further control. As a result, raw, non-stabilized sludge with a high pathogens content is used in the food chain without any proper control [24]. In addition, Egypt is facing challenges for proper disposal and management of sludge, owing to the limited available resources as well as technical expertise. In light of the government’s new policy of vision 2030, the attention to sludge management and disposal has

Table 2
Overview of water and wastewater treatment services in Egypt.

Drinking water supply	
Number of drinking water treatment plants	2720
Total drinking water	~28 million m^3/day
Average water coverage	97%
Sanitation coverage	
Number of wastewater treatment plants (WWTPs)	415
Total treated wastewater	~12 million m^3/day
Average sanitation coverage	57% (~90% in urban areas & ~35% in rural areas)

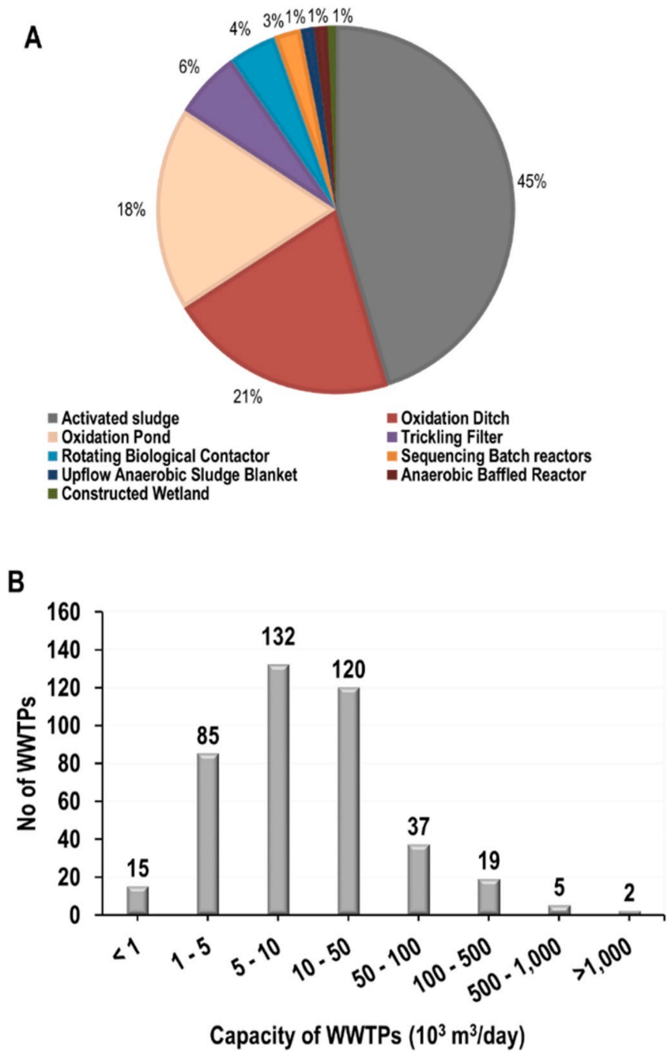

Fig. 1. (A) Technologies used for wastewater treatment in Egypt. (B) Number of WWTPs in Egypt based on the wastewater treatment capacity.

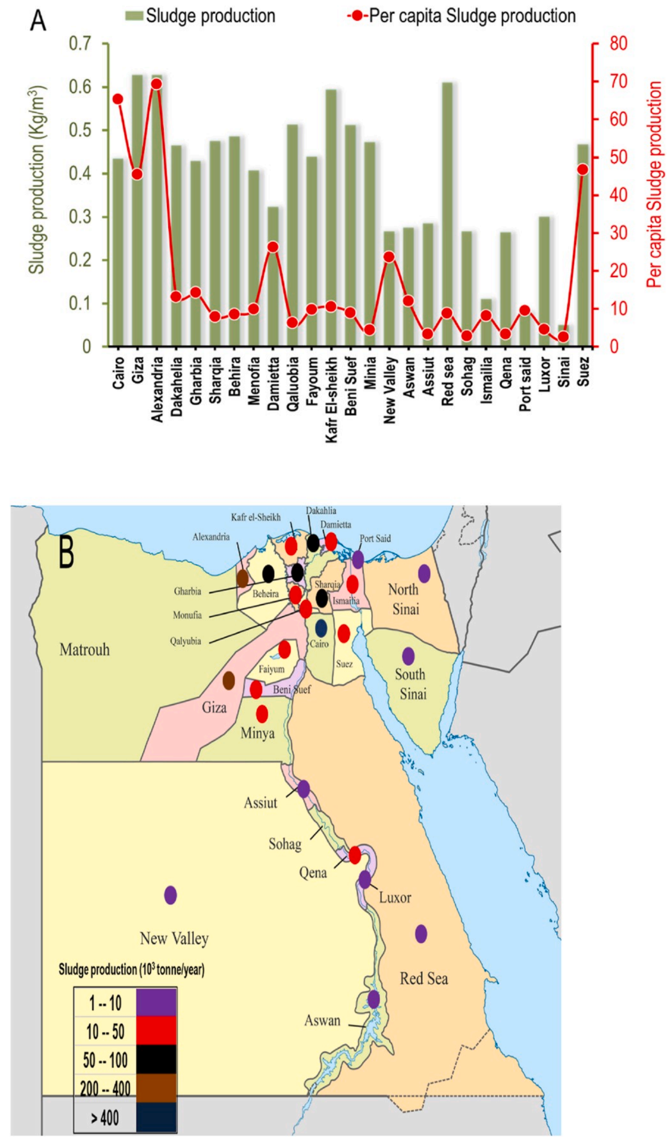

Fig. 2. (A) Total sludge production and per capita sludge production in Egypt. (B)The geographic distribution of sludge production in Egypt.

significantly increased, mainly due to minimize the high risks associated with the current disposal technologies and to produce renewable, clean energy [32]. Therefore, the Egyptian government is currently working toward accelerating the adoption of disposal technologies that have the ability to convert municipal wastewater sludge into outputs of high value to the users, including renewable energy and fertilizers for agricultural purposes [28,29].

3.2. Sludge quality and characteristics

Table 3 shows the typical composition of mixed (primary and secondary) sludge from WWTPs in the 5 governorates (i.e., Cairo, Giza, Alexandria, Sharqia, and Kafr El-Sheikh) that generate ~ 75% of sludge in Egypt. The organic matter percentage varied between 40 and 70% with an average value of 51 ± 13%. The large differences are most likely due to the different ratios of primary and secondary sludge in the final sludge samples, change in organic matter concentration in the influent wastewater, and the technologies used for wastewater treatment. The average total nitrogen (TN), total phosphorous (TP), and potassium (K) concentrations in the sludge are 1.21 ± 0.40%, 0.70 ± 0.20%, and 0.18 ± 0.10%, respectively. The relatively high organic matter and nutrients content in sludge open up new opportunities to use the excess sludge as a renewable source to produce biogas and soil fertilizers/conditioners for supporting the growth of agricultural crops only after ensuring compliance with national legislations for sludge disposal/reuse. Although sludge generally has a lower nutrients content than commercial fertilizers, their low costs represent an important economic advantage to replace commercial chemical fertilizers, minimizing the costs associated with agricultural activities, and the negative impacts of high nutrients levels entering the environment in an uncontrolled manner. In addition, the slow-release and long-term availability of nutrients in sludge can improve the cropping efficiency compared to commercial fertilizers [8,9,33].

Table 3
Organic matter and nutrients concentrations in municipal wastewater sludge (n = 56).

Parameter	Average ± SD[a]	Range
Organic matter (OM)%	51 ± 13	40–70
Total Nitrogen (TN)%	1.20 ± 0.40	0.50–1.70
Total phosphorous (TP)%	0.70 ± 0.20	0.30–0.80
Potassium (K)%	0.20 ± 0.10	0.10–0.30

[a] SD is standard deviation.

Despite the economic benefits of using sludge for renewable energy production and land reclamation, there is a need to comply with restrictions for pathogens or potentially-pathogenic organisms. Due to the lack of any sludge stabilization facilities in the majority of WWTPs in Egypt, the current excess municipal wastewater sludge is expected to have a high content of pathogens, representing the most critical obstacles for safe use in agriculture [34,35]. For all analyzed samples, *Ascaris* was not detected; however, the indicator organisms faecal and total coliform were present at relatively high values (1.8×10^4 to 1.6×10^9 MPN/100 mL), showing the importance for establishing sludge stabilization facilities to achieve high pathogens inactivation for safe reuse.

National regulations consider heavy metals as one of the major sources of contaminants in municipal wastewater sludge, especially when the sludge is being utilized for agricultural purposes. The main source of heavy metals in sludge is the unregulated discharge of industrial effluents to municipal sewers [36]. In Egypt, ~15% of WWTPs (i.e., 63 WWTPs) receive mixed domestic and industrial effluents due to unregulated discharge of nearby industrial facilities (Fig. 3). Gharbia governorate has the highest number of WWTPs that receive mixed effluent; however, WWTPs in Cairo governorate has the highest daily wastewater capacity (i.e., 1,685,000 m^3 per day). Table 4 shows the average concentration of heavy metal in sludge samples collected from WWTPs in Cairo governorate. All observed values were under the national standard limit that regulates the use of municipal wastewater sludge in agricultural purposes. Due to the low industrial wastewater flow to the sewerage, the heavy metals content in municipal WWTPs in other governorates are expected to be much lower compared to those in Cairo governorate's WWTPs, where industrial activities are more concentrated. However, there is a growing interest in establishing new WWTPs (e.g., WWTP in Qiwesna industrial zone, Menoufia governorate in the northern part of Egypt) that receive only industrial effluent to minimize the health risk associated with discharge industrial effluents into sewerage systems.

3.3. The current disposal methods of sludge

Considering the high potentials for bio-energy recovery and useful value-added products, and the challenge of operating cost-effective wastewater treatment processes, proper sludge management in Egypt is not an option but a necessity. However, the selection decision for specific technologies for sludge handling and disposal is challenging, and has to be taken based on economic, technical, and social considerations [37–39]. Currently, proper sludge management in Egypt is poor, with about 85% of sludge being sold directly to local vendors without proper treatment [24,40]. The main obstacles for implementing a proper sludge management strategy are related to socio-economic aspects rather than to technical limitations. There are various suitable technologies available for the treatment, dewatering and disposal of sludge

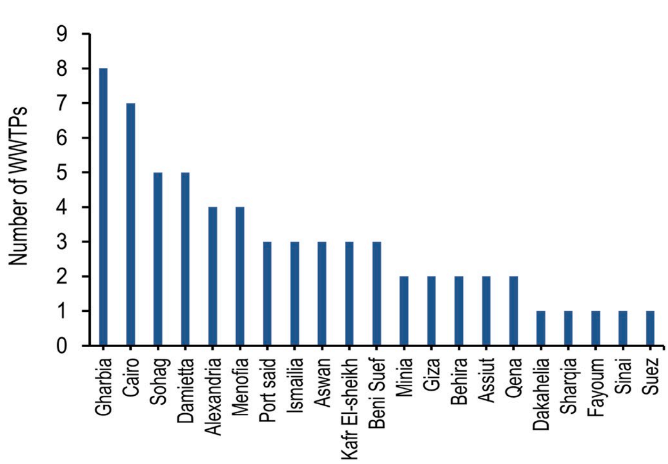

Fig. 3. WWTPs that receive mixed domestic and industrial effluent.

and for the recovery of value-added resources (e.g., renewable energy and fertilizers production). However, the lack of a socio-economic design to identify and deploy the most-sustainable technological approach in a given cultural and geographic context hampers any implementation in this field. Therefore, there is an urgent need to develop management and business scenarios for sludge management in Egypt, which require adapted management routes that are capable of maximising the resources recovery benefits. Moreover, there is an urgent need to encourage national and international business associations to invest in this potential sector.

In Egypt, the current scenario for sludge disposal, which is implemented in the majority of wastewater treatment plants in Egypt, can be presented as follows: mixed sludge (primary and secondary) is pumped into thickeners, mainly gravity thickeners, to increase the solids content from 1–2% to 4–6%. Then, the thickened sludge is pumped into natural drying basins to increase the concentration of dry solids to 40–50%. The required time to achieve a high dewatering efficiency ranges from 2 to 3 weeks during summer (i.e., an average temperature of 40 °C) and 6–8 weeks in winter (i.e., an average temperature of 10 °C). In several WWTPs, chemical conditioning is applied, which includes the addition of organic polymeric electrolytes (e.g., polyacrylamide) and/or inorganic coagulants (e.g., iron salts and lime). Alternatively, sludge stabilization is achieved through one of the following technical stabilization approaches: (1) mesophilic anaerobic digestion; (2) anaerobic co-digestion with other organic waste streams; (3) windrow composting; and (4) storage lagoons.

3.3.1. Sludge stabilization using anaerobic digestion (AD)

Since decades, AD has shown a promising opportunity to produce renewable energy, in forms of biogas, by the anaerobic biotransformation of complex organic matter in sludge via a variety of volatile organic acids into biogas, a mixture of methane (CH_4) and carbon dioxide (CO_2) by methanogens. The biogas can be subsequently combusted in a separate combined heat and power (CHP) unit to generate electricity, at electric conversion efficiencies of about 35–40% [41]. This methanogenic biotransformation is a complex natural microbial process, which is applied worldwide to stabilize organic matter and to recover the biochemically-stored energy for local reuse [42].

The AD process is very robust and is generally applied at municipal wastewater treatment plants in industrialized countries to minimize fossil fuel consumption. In Europe, about 50% reduction in fossil fuel consumption can be achieved by applying AD technology. In addition, current developments aim at maximising bio-energy recovery via AD in order to achieve energy neutrality at the WWTP. Efficient use of biogas as well as the recovery of nutrients and stabilized organic matter from sludge represent: (i) A potential operational cost recovery; (ii) A source of 'green' energy supporting the reduction of greenhouse gases (GHGs) emissions and the carbon footprint; (iii) A helping hand in the current energy shortage in Egypt that constraints wastewater treatment process, in which the recovery of biogas would minimize the use of fossil fuels at WWTPs; and (iv) an effective low-cost replacement for chemical fertilizers, new land reclamation, and desert soils conditioners [3,43–45].

The first anaerobic digester for sludge stabilization in Egypt was established at the Gabal Al-Asfar WWTP in the northeast side of Cairo governorate, which is the largest WWTP in Egypt and one of the largest WWTPs worldwide. The current wastewater treatment capacity of the Gabal Al-Asfar WWTP is ~2.5 million m^3/day, with the expectation to increase it to 3.5 million m^3/day in 2037 [46–48]. In the Gabel Al-Asfar WWTP, the mixed (primary and secondary) municipal wastewater sludge is pumped into gravity thickeners to increase the solids content to ~4%. The thickened sludge (i.e., 14,000 tonnes per day) is then pumped into primary anaerobic digesters with a solids retention time (SRT) of 20 days. The digested sludge is transported into secondary digesters with a shorter SRT (i.e., 7 days). After a mechanical dewatering step using belt filter press units, the digested sludge (i.e., ~21% dry solids) is pumped into natural drying basins to increase the concentration of dry solids to

Table 4
Heavy metals (mg/kg) in dried municipal wastewater sludge.

WWTP	Concentration (mg/kg)							
	Pb	Fe	Cr	Cu	Ni	Zn	Co	Cd
Al Berka	12.5 ± 0.3	83.7 ± 4.5	38.3 ± 8.2	43.9 ± 10.2	1.1 ± 0.3	103.3 ± 23.1	N.D.[a]	N.D.[a]
Arab Abu Sa'ed	9.6 ± 0.5	62.4 ± 3.5	20.6 ± 5.6	15.8 ± 4.3	1.2 ± 0.4	61.8 ± 14.2	N.D.[a]	N.D.[a]
Baleks	8.5 ± 0.3	34.8 ± 6.1	27.9 ± 7.8	40.7 ± 7.3	9.3 ± 0.9	83.5 ± 16.2	N.D.[a]	N.D.[a]
6th October	29.1 ± 0.6	107.8 ± 9.2	115.9 ± 11.2	97.18 ± 15.6	16.2 ± 2.4	164.1 ± 30.1	N.D.[a]	N.D.[a]
National standard	**300**	–	**1200**	**1500**	**420**	**2800**	–	**39**

[a] N.D.: not detected.

60–80% before its use in agriculture. The current production rate of biogas, which contains approximately 60% methane, exceeds 125,000 m^3/day. This biogas is then combusted in a separate combined heat and power (CHP) unit to generate about 12 MW of electricity, representing ~ 65% of the total electrical power demand of the entire WWTP. Due to the promising consequences of using AD in sludge stabilization in the Gabel Al-Asfar WWTP, there is a growing interest in establishing new AD facilities in other WWTPs in Egypt, especially for WWTPs with high wastewater treatment capacity.

Owing to the successful operation of anaerobic digesters for sludge stabilization in Egypt, there is a current plan to establish anaerobic digesters at the New Cairo WWTP (in Cairo governorate), which receives about 40,000 m^3/day. Although the anaerobic digesters have not been fully functional yet, the amount of processed sludge is expected to exceed 2000 m^3/day that produces ~1700 m^3 of biogas daily [49]. In addition to the obvious advantages of AD (such as renewable energy production and minimizing the greenhouse gas emissions) over other sludge disposal technologies, implementation of well-functioning AD facilities would reduce the (non-controlled) environmental pollution due to the improper sludge disposal in Egypt [40,50].

3.3.2. Sludge stabilization using anaerobic co-digestion

Although the anaerobic digestion of sludge is widely used as a means to recover methane from sludge, the anaerobic co-digestion of sludge and food wastes offers even more interesting opportunities for retrofitting the conventional anaerobic digesters due to the much higher digestion rates and methane recovery potentials, when well-digestible food waste, for example, is included [51–53]. Anaerobic co-digestion provides several advantages over conventional anaerobic stabilization of sludge, such as higher biodegradable organic matter and nutrient contents, dilution of toxic compounds in sludge, and enhancing the synergistic effects of microorganisms [54–56].

The first demonstration full-scale plant for co-digestion of sludge in Egypt was established in April 2018 by Empower Co. at the Sakha WWTP in the Kafr El-Sheikh governorate. Since the co-digestion is still in the testing stage, the co-digestion digester could dispose ~ 185 tonnes per day of combined municipal wastewater sludge and organic matter-rich solid wastes, such as chicken manure, plant residues, and household waste, collected from the nearby districts. The sludge and organic matter-rich solid wastes mixture is converted into biogas, which is subsequently converted into electricity using a combined heat-power generator. Moreover, the produced biosolids are hygienized and sold as Class A biosolids to the farmers. This partnership is unique in Egypt and may result in a blueprint approach for other locations. In addition to the energy benefit, the hygienic quality of the sludge is ensured by the company. As such, a better grip on the supply chain is attained. Moreover, Empower Co. plans to establish 6 co-digestion facilities in the Kafr El-Sheikh governorate in the coming few years, generating ~ 6 MW of electricity output in total.

3.3.3. Sludge stabilization using windrow composting

The windrow composting of dried municipal wastewater sludge gained attention as a means of sludge stabilization for agricultural reuse as it was recently applied in the "9 N" site in the Alexandria governorate. The 9 N site, which is located 45 km southwest of Alexandria, is the central facility for sludge treatment and stabilization. It has been operated since 1997 with composting windrow processes; however, it was reportedly closed for 5 years (from 2012 to 2017) due to odour complaints and hygienic concerns about groundwater contamination [40,57].

During normal operation, mature compost is mixed with fresh dewatered sludge transported from WWTPs with a ratio of 1.5:1 in long-parallel rows (i.e., 250 m length each) using mechanical shovels for mixing the mature compost to act as a bulking agent to improve the composting process. The duration of the composting process ranges from 4 weeks (in summer season) to 2 months (in winter season). At the end of each compositing cycle, the compost is stored in stockpile areas for several weeks/months prior to its sale and reuse [57].

Alexandria governorate has 21 WWTPs, with wastewater treatment capacity ranging between 1200 m^3/day to 600,000 m^3/day. The largest WWTPs are the east-Alexandria WWTP – with an actual wastewater treatment capacity of 600,000 m^3/day – and the west-Alexandria WWTP – with an actual wastewater treatment capacity of 370,000 m^3/day. In both WWTPs, only primary treatment is applied, with an expectation to be upgraded to secondary treatment (activated sludge-based system) in the coming few years [58,59]. The primary sludge from both WWTPs (i.e., 3000 m^3/day, conc. of 4% DS) are mechanically dewatered by belt filter press units, and chemically dewatered by using polymers (2–4 kg/ton DS) to increase the sludge solids to 20–30%. Then, the dried sludge (800–1000 tons/day) is transported using trucks for stabilization using windrow-composting facilities at the 9 N site. The produced sludge from other small WWTPs is dewatered by centrifugation before its transportation into 9 N site for stabilization. The annual compost production is expected to exceed 100,000 tonnes, with a relatively-low organic content (34%) and high content of nutrients (3% total nitrogen and 175 mg/kg phosphorus) [57].

3.3.4. Sludge stabilization using storage lagoons

Another method for sludge stabilization is sludge storage lagoon, which is established in Giza governorate. Two of the largest WWTPs in Egypt are the Abu Rawash WWTP and Zenin WWTP, which are located in Giza governorate, with a wastewater treatment capacity of 1,500,000 m^3/day and 450,000 m^3/day, respectively. The mixed municipal wastewater sludge generated from the conventional activated sludge system in the Zenin WWTP (~ 14,000 m^3/day with a concentration of 1%) is pumped via pipelines into the Abu Rawash WWTP, where it is mixed with sludge generated from the primary treatment facilities at the Abu Rawash WWTP (~ 6000 m^3 per day with DS concentration of 4–5%). The mixed sludge is pumped over a distance of ~40 km into sludge stabilization lagoon (20 lagoons with an area of 500–600 acres), which is located west of Cairo-Alexandria highway road. During the long duration of storage (ranging from 1 to 4 years), the organic matter gets decomposed and pathogens are inactivated, leaving stabilized sludge that can be used safely in agricultural purposes [60]. The annual compost production is about 20,000–25,000 tons, with a relatively-high solids content (60–70%).

3.4. Current legislation of sludge management in Egypt

3.4.1. The institutional framework of the water and sanitation sector

In 1956, two companies were nationalized in Cairo and Alexandria governorates to provide and manage drinking water and sanitation services. In order to promote the investments in both governorates, two state agencies were established to manage drinking water supply (General Organization for Potable Water (GOPW)) and sanitation services (the General Organization of Sewerage and Sanitary Drainage (GOSSD)). Under the provisions of Presidential Decree 137/1981, National Organization for Potable Water and Sanitary Drainage (NOPWASD) was established by merging the GOPW and the GOSSD to be the executive agency for the water and wastewater sector in Egypt; to prepare designs and supervise the construction of projects at the national level; and to establish standards for the waste/wastewater sector. In addition, it has taken the responsibility of operation and maintenance for the drinking water and wastewater treatment plants, utility mapping, water meter repair and calibration, and disinfection by ozone generation on site.

From 1981 to 1991, the Ministry of Housing and Public Utilities (MHPU) and NOPWASD have operated in an environment of change. As a result, externally-funded, massive investments significantly increased to improve safe access to drinking water supply and sanitation services. For instance, the drinking water production increased by 3.8-fold (i.e., from 5.5 million cubic meters (MCM) per day in 1982 to 21 MCM in 2004). However, the organizations in charge of operating and maintaining the water and wastewater facilities were weak, in terms of human and financial resources, leading to overall poor quality services.

In 2004, the Holding Company for Water and Wastewater (HCWW) was established to manage and owe all water and wastewater utilities in Egypt under the provisions of Presidential Decree 135/2004. The Egyptian government is the primary, and, in most cases, the sole water and sanitation services provider. Through its affiliated companies in the Egyptian governorates, HCWW is the primary party that is officially responsible for operation and maintenance of water supply and sanitation facilities, and installation of house connections in Egypt.

The Egyptian Executive Agency for Water and Wastewater has been created in 1981 and takes the responsibility of the planning, designing and the installation of water and wastewater projects. It is part of the Ministry of HPU. The Executive Agency for Water and Wastewater is part of HCWW and is responsible for supervising the construction and commissioning of water and wastewater treatment plants from tender documents, as well as reviewing the tenders until complete finalizing the construction process and evaluation stage.

Within the organizational structure of HCWW, there are affiliated water/wastewater companies that own, manage, and operate the water and wastewater facilities in Egypt. In each affiliated company, there is an administrative unit that is responsible for the management of the sanitation and wastewater sector, including sludge handling, disposal, and selling. For the majority of affiliated companies, the sanitation management sector is less developed than the drinking water management sector. Generally, wastewater and sanitation sector is suffering from many issues, including limited financial support, lack of public awareness, limitation in human resources and well-trained operators, reliance on manual systems, and lack of coordination and collaboration between different water and wastewater authorities [27]. In particular, sludge handling and disposal get a little attention, mainly due to the limited space and financial means to construct any sludge stabilization facilities; and more importantly, due to the current vision of the decision makers in many affiliates of the HCWW that municipal wastewater sludge is a serious problem that needs to be solved by getting rid of it for a low price or even for free [61]. The vendors usually use the municipal wastewater sludge directly as a fertilizer for land reclamation without any further treatment or storage, although the national legislations force the end users to store the sludge for up to 6 months prior to the use in the land application as well as to not use the sludge in edible vegetables and fruits. However, there is no national organization, including the Ministry of Health and the Ministry of Agriculture that has the right to analyse the sludge before its use in the land application. In fact, the quality of the produced sludge to ensure its compliance with the national regulation for reuse in agricultural purposes is hardly addressed, although HCWW and its affiliated companies have fully-equipped laboratories that are dedicated to wastewater and sludge analysis.

3.4.2. National legislations for sludge disposal/agricultural use

Over the past few decades, Egypt has been focussing on drinking water supply and sanitation-related services, especially constructing new sewerage networks and wastewater treatment facilities, with a little attention given to the management of excess sludge produced from municipal wastewater treatment [62–64]. This is reflected in the local regulatory standards and legislations that is often imported from more industrialized countries without any attempt to adapt it to local situations.

Municipal wastewater sludge can be defined as the final solid product of municipal wastewater treatment. The Law 38/1967 classifies municipal wastewater sludge as non-dangerous solid waste that has to be properly disposed of. Ministerial decree 254/2003 (as of 8th chapter of decree 44/2000) was issued to encourage the municipal sludge reuse, especially for agricultural purposes, only after proper handling and treatment to prevent any harmful impact on human health, soil, and vegetation [65]. Otherwise, the untreated sludge has to be either landfilled in a sanitary landfill or incinerated with compliance with the environmental precautions and legalizations.

Law 48/1982 and ministerial decree 44/2000 regulates the use of sludge for agricultural purposes only. For sludge use, the regulations only consider heavy metals and pathogenic (or potentially-pathogenic) organisms as the only sources for contaminations (Table 5). The law (as well as ministerial decree) obligates the end user to store sludge for 6 monhs before land applications. However, the highly-contaminated sludge (i.e., sludge from WWTs receiving mixed municipal and industrial wastewater) with heavy metals or pathogenic organisms have to be landfilled properly.

In Egypt, sludge is widely used for agricultural purposes, despite the hygienic concerns due to the high contents of heavy metals, pathogens, and toxic organic contaminants. Taking into consideration the importance of agriculture in Egypt, especially the current plan of the Egyptian government to inaugurate the phase 1 of 1.5 million-feddan (feddan is equivalent to 4200 square meter) the reclamation project, the agricultural use of (stabilized) municipal wastewater sludge seems to be an attractive and potentially beneficial option under the Egyptian conditions. However, its use has to be controlled to minimize public and environmental health hazards such as the potential surface and groundwater contamination.

Table 5
Law 48/1982 and decree 44/2000 limits for the use of sludge in agriculture.

Item	Unit	Value
Zn	mg/kg	2800
Cu	mg/kg	1500
Ni	mg/kg	420
Cd	mg/kg	39
Pb	mg/kg	300
Hg	mg/kg	17
Cr	mg/kg	1200
Mo	mg/kg	18
Se	mg/kg	36
AS	mg/kg	41
F. Coliform	CFU/gm	1000
Salmonella	cell/100 mL[a]	3
Ascaris	cell/100 mL [b]	1

[a] at 4% solids content of sludge;[b] at 5% solids content of sludge.

3.5. Evaluation of the potential scenarios for sludge disposal in Egypt

We used the DSS methodology to evaluate which scenarios would be beneficial for sludge management and disposal in Egypt. Table 6 reveals that AD is the most sustainable strategy for sludge disposal followed by sludge disposal and use in agricultural activities and anaerobic co-digestion. AD has the potential to achieve a high degree of sludge stabilization and reduction of sludge quantity along with the conversion of organic matter to biogas as well as several value-added products (such as soil conditioner and fertilizers). Moreover, the application of AD would eliminate the need of establishing new sanitary landfills for sludge disposal, since the land availability is scarce, especially in the Nile delta (in the northern part of Egypt). Consequently, several anaerobic digesters are planned to be installed and operated in the coming 5 years in collaboration with private sector associations, especially in Cairo, Alexandria and Kafr El-Sheikh governorates. Anaerobic digestion of organic wastes, including sludge, has been used for a wide range of waste flow rates (ranging from a few hundred m^3/day up to thousands m^3/day).

Following the AD option, the sludge disposal and use in agricultural activities seems to be favorable in all the evaluating categories of the DSS framework, mainly due to its relatively-low investment cost and high nutrients content [66]. In addition, there is a wide acceptance among stakeholders and end users to use municipal wastewater sludge for land application.

Another interesting option for sludge disposal in Egypt is anaerobic co-digestion. Although anaerobic co-digestion, as a means of municipal wastewater sludge disposal and renewable energy production, has become a promising option with a wide application in developed countries [67,68], the technology remains in its initial stage of implementation in Egypt. One factor that limits its implementation in Egypt is the relatively-high cost of transportation of organic wastes into the sludge disposal sites; thus, it is obvious that anaerobic co-digestion of municipal wastewater sludge could be a suitable option for sludge disposal in rural areas, i.e., Nile Delta. In addition, the implementation of anaerobic co-digestion near residential areas could face social rejection from stakeholders and end users, since it has a moderate risk to society and the environment.

Although sludge stabilization via sanitary landfill represents a low-cost, environmentally-friendly option, the large land requirement and the lack of any regulatory landfill standards slow down the wide application of this disposal method in Egypt. Accordingly, in Egypt, the use of sanitary landfill for waste streams disposal, including municipal wastewater sludge, is still in its infancy [40].

Despite the promising results of the simplified, qualitative DSS tool, which would be easily used and implemented to get a preliminary evaluation of the potential sceneries for managing and disposing municipal wastewater sludge in Egypt, it is recommended to implement a thorough, quantitative DSS study by including more evaluating categories and attributes in order to enhance the evaluation stage.

Selecting the appropriate sludge disposal technology is a multifaceted challenging task, which has to meet several criteria, including the efficient recovery of value-added products, high efficiency for contaminates removal, and low capital and O&M costs [69,70]. However, the available economic data of municipal wastewater sludge disposal in Egypt is scarce. A preliminary economic study suggested that the AD stabilization of municipal wastewater sludge would be beneficial for medium-to large WWTPs with capacities exceeding 8000 m^3/day, while for smaller WWTPs, such as in Nile Delta, the natural drying beds followed by agricultural reuse would be the most sustainable option to dispose sludge for the Egyptian situation [71]. Thus, it might be not possible to establish an anaerobic digester in each WWTP, and alternatively, building centralized stabilization facilities would allow achieving economic revenues, taking in consideration the costs of sludge transportation to the stabilization facilities. The situation in bigger governorates (e.g., Cairo and Alexandria) is much easier, since the majority of

Table 6
Results from the DSS analysis applied to the case study of Egypt.

Category	Attributes	Anaerobic digestion	Aerobic composting	Anaerobic co-digestion	Agricultural reuse	Landfill
Economic aspects	Investment cost	Yellow	Yellow	Yellow	Green	Yellow
	O & M cost	Green	Yellow	Yellow	Yellow	Yellow
	Profit	Green	Yellow	Green	Green	Red
Socio-cultural aspects	Social acceptance	Green	Yellow	Green	Yellow	Yellow
	Heavy metals-associated risks	Yellow	Yellow	Yellow	Yellow	Yellow
	Pathogen-associated risk	Yellow	Yellow	Yellow	Yellow	Green
	Emissions	Yellow	Yellow	Yellow	Yellow	Yellow
Environmental aspects	Recovered value-added products	Green	Yellow	Green	Green	Yellow
	Solids residues to be disposed	Green	Yellow	Green	Yellow	Red
	Land requirement	Yellow	Red	Yellow	Yellow	Green
	Transportation	Green	Red	Red	Yellow	Yellow
	Odors	Yellow	Red	Yellow	Yellow	Red
	Noise	Yellow	Yellow	Yellow	Yellow	Yellow
	Heavy metal emission risk	Yellow	Yellow	Yellow	Yellow	Yellow
	Pathogen emission risk	Yellow	Yellow	Yellow	Yellow	Yellow
	Air emission risk	Yellow	Yellow	Yellow	Green	Red
Technological aspects	Reliability	Green	Yellow	Green	Green	Yellow
	Flexibility and modularity	Green	Yellow	Green	Green	Yellow
	Complexity	Yellow	Yellow	Yellow	Yellow	Yellow
	Personal requirements	Yellow	Yellow	Yellow	Yellow	Green
	Reagents consumption	Yellow	Yellow	Yellow	Yellow	Yellow
	Energy consumption	Yellow	Yellow	Yellow	Green	Green
Overall ranking		Green	Yellow	Yellow	Yellow	Yellow

WWTPs have a high wastewater treatment capacity and the infrastructure for such a stabilization facility is available. Although excess sludge has relatively low biodegradable organic content, digestion rates can be significantly enhanced by applying co-digestion of municipal wastewater sludge with concentrated and nutrient-rich waste streams, such as food and market waste, animal manure and farm wastes. In summary, AD technology seems to be a sustainable option for sludge management and disposal in Egypt as well as producing renewable energy. For example, if the AD approach is used for the sludge disposal produced in Egypt, approximately 1.6 billion m^3 of biogas can be produced per year, which could be used to generate up to 3.0 MWh of electricity per year.

Another challenge facing the application of AD technology for sludge stabilization is the low market value of its end product (i.e., biogas) with <60% CH_4 content. Nonetheless, biogas can be perfectly used for combustion in biogas motors and CHPs. An interesting approach to improve the output of anaerobic digestion of sludge is biogas upgrading to biomethane, which can be later compressed for gas-grid injection or used as a renewable natural gas, or as automotive fuel [72,73]. The biomethanization process requires gas purification by removing CO_2, moisture and other contaminants, which is expensive (i.e., 5.50–11.50 USD per 1000 standard cubic foot (scf) or ~ 28 m^3 of biomethane) and technologically-sophisticated process, especially for developing countries, such as Egypt [74].

In 2016, Egypt revised the feed-in-tariff program for renewable energy projects to support small- and medium-scale renewable energy industry, mainly for solar power and wind industry, which provides electricity price compensation of ~ 126 USD per MWh for output of up to 200 KW and ~ 136 USD per MWh for a capacity of 200–500 KW [75,76]. The target is to produce ~20% of electricity from renewable energy resources before the end of 2020 [40,77]. Therefore, it is advised to use the current public–private partnership (PPP) experiences to develop an Egyptian 'Code for Excess Sludge Handling', which takes care about preventing non-controlled uses of excess sludge, while facilitating the recovery of energy and other resources from the mentioned biomass streams that will rapidly grow in volume coming decades.

4. Outlook and future perspectives on sludge disposal in Egypt

This research provides an overview of the current practice of municipal wastewater sludge management and disposal in Egypt as well as the barriers that might hinder the application of appropriate handling methods for sludge. It seems that the main obstacles for municipal wastewater sludge disposal in Egypt are institutional and governing rather than technological. In addition, the lack of regulatory and legal frameworks limit the deployment of suitable disposal method, especially in rural areas, except for a few numbers of projects [40]. The high cost associated with sludge handling and disposal – up to 50% of the O&M cost of the entire wastewater treatment plants [1,2] – as well as that wastewater treatment in Egypt is highly subsidized and financially supported by the government are also another obstacles for establishing sludge disposal facilities in each WWTP. The low wastewater tariffs and low rate of resources recovery from wastewater make the wastewater treatment process in Egypt expensive process [63]. Therefore, it is necessary to launch various financial, business-oriented schemes in collaboration with non-traditional stakeholders, such as private sector and civil society, to improve the current status of the wastewater treatment process, including sludge handling and disposal. However, the shortage of qualified personnel to operate and manage WWTPs, including sludge stabilization facilities, slows down achieving sustainable wastewater treatment process. Thus, it is necessary to involve the educational and research institutions to train workers and transfer knowledge related to wastewater and sludge treatment.

5. Conclusions

Managing and disposing the municipal wastewater sludge in Egypt is critically important to eliminate the risks of the non-stabilized sludge in land reclamation, minimize the potent greenhouse gases emissions, and recover value-added products (such as renewable energy, soil conditioners, and nutrients). However, evaluating the feasibility as well as economic tradeoffs of any disposal technology is not possible with the absence of spatially-resolved estimates of sludge production. Approximately 2.1 million tons DS is produced in 2018 annually and the average per capita sludge production is ~ 17.1 kg, which is comparable with values reported for industrialized countries. Owing to the high population density and urbanization in the northern part of Egypt, the majority of sludge production (i.e., ~70%) is generated only from 3 governorates (i.e., Cairo, Giza, and Alexandria), with a little amount generated from WWTPs in the Southern part, mainly due to the low wastewater capacity and the application of waste stabilization ponds for wastewater treatment. Despite the importance of managing the use of treated sludge, especially for agricultural purposes, the national legislations for sludge disposal/reuse in Egypt are incomplete and, in practice, they are not reinforced.

The current scenario for sludge treatment and disposal includes sludge dewatering and thickening, after which the sludge is sold to vendors for agricultural purposes. Alternatively, sludge stabilization is achieved through one of the following technical stabilization approaches: (1) mesophilic anaerobic digestion; (2) anaerobic co-digestion with other organic waste streams; (3) windrow composting; and (4) storage lagoons. Due to lack of financial resources and limited areas, there are no sludge stabilization facilities in the majority of WWTPs in Egypt; with nearly 85% of (non-stabilized) sludge in Egypt being improperly used in agriculture.

However, the selection of a suitable sludge disposal technology remains challenging due to institutional, social, economic, and technical barriers. Therefore, it is recommended to develop a transitional, non-conventional management plan that focuses on reforming the managing governmental organizations, and regulatory standards and laws (i.e., top-down approach) and partnering with non-traditional stakeholders (such as private sector and civil society) and collaborators (such as research and educational institutions) (i.e., bottom-up approach). The "sludge-to-energy" approach using an AD-based technology seems to be favorable with several benefits, including the high degree of sludge stabilization and sludge quantity reduction along with the conversion of organic matter to biogas as well as several value-added products (e.g., soil conditioners and fertilizers). Such an approach might be established by collaboration with the private sector to maximize the economic trade-offs and environmental benefits. In addition, it is required to take other immediate actions, including: (1) improve the sanitation coverage, especially in rural areas; (2) improve the efficiency of the current WWTPs; and (3) develop an Egyptian "Code for Excess Sludge Handling and Disposal".

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Rifaat Abdel Wahaab: Conceptualization, Resources, Writing - review & editing, Formal analysis. **Mohamed Mahmoud:** Conceptualization, Methodology, Investigation, Writing - original draft, Visualization, Formal analysis, Project administration. **Jules B. van Lier:** Conceptualization, Resources, Writing - review & editing, Formal analysis, Supervision.

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