Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2019.23286

139 (2019) 95–104
January

Developing a decision support tool for managing sludge from wastewater treatment plants in Jordan

H.A. Abu Qdais

Civil Engineering Department, Jordan University of Science and Technology, , P.O. Box 3030, Irbid, 22110, Jordan, email: hqdais@just.edu.jo (H.A.A. Qdais)

Received 5 May 2018; Accepted 15 October 2018

ABSTRACT

This study is aiming at helping the decision makers in Jordanian water sector to address the selection of optimal sludge management alternative of the generated sludge at the wastewater treatment plants. Multi criteria analytical hierarchy process (AHP) was used to develop an AHP model that has a goal to select the optimal sludge management alternative. The AHP model comprised three main criteria, nine sub criteria and five sludge management alternatives. The analysis revealed the following preference order of the sludge management alternatives: energy recovery from the sludge is the most preferred option, followed by composting, then disposal without treatment, evaporation ponds and finally the least preferred alternative is using the sludge for the production of building materials. Dynamic sensitivity analysis based on -what if scenario- revealed that decreasing the weight of environmental criteria by 7% has not changed the ranking, however the weights of criteria have been changed. The most sensitive alternative appeared to be the energy recovery alternative, while the least sensitive ones are the composting and production of building materials.

Keywords: Sludge management; Decision support tool; Wastewater; Analytical hierarchy process; Jordan

1. Introduction

Sludge is a byproduct of wastewater treatment processes. It contains relatively high concentrations of solids (both organic and inorganic) and microorganisms. Unless properly managed, sewage sludge may cause environmental and public health problems [1]. In order to comply with stringent environmental regulations, sludge should be subjected to treatment. For example, in EU countries, 50% of the operational cost of the wastewater treatment plants of secondary treatment is attributed to sludge management and disposal processes [2]. According to Nowak [3], the cost of sludge disposal and treatment comprising 30% of the total investment cost of the wastewater treatment plant and 50% of the total operational cost for municipal treatment plants that serve between 5000 to 200,000 population equivalents. Management of sludge represents a serious challenge for the treatment plants and has become an important concern worldwide [1]. However, there is no universal solution to the sludge management that considers local circumstances and plans of sustainability for each country [4]. Therefore, every country has to decide the path to follow for sludge management [3].

This is particularly true for the case of Jordan, where in 2004 there were 24 wastewater treatment plants produced 260,000 m^3 of liquid sludge and 12,000 m^3 of dewatered biosolids [5], while in 2010 the number of treatment plants has increased to 31 plants which has led to increase in the amount of the produced sludge and biosolids to reach annually about 300,000 m^3 and 15,000 m^3, respectively. Most of the treatment plants are applying the solar drying beds to dewater the sludge which is either hauled for disposal in landfills or stored on site as dried sludge (biosolids) [6]. For example, at Al-Samra treatment plant (the largest plant in the country that treats 65% of the generated wastewater in Jordan) 500,000 m^3 of biosolids have been accumulated.

Different countries have tested and applied various management and disposal options of the sludge that are suiting

*Corresponding author.

1944-3994 / 1944-3986

their local circumstances. As for Jordan, the task of selecting sludge management alternatives will be considered in this research, by developing a multi criteria decision support system. The Analytical Hierarchy Process (AHP) will be applied in prioritizing the selection of the sound sludge management option for the wastewater treatment plants.

Hassouneh et al. [7] indicated that the municipal sludge handling is a major problem facing wastewater treatment plants. To find a solution for sludge management in Jordan, the researchers investigated the possibility of sludge stabilization via composting. Samples of sludge from drying beds were obtained from Salt wastewater treatment plant and subjected for composting. Both static aerated pile and windrow composting systems were tested on a pilot scale. It was concluded that the stabilization of organic matter in aerated static pile was faster than the windrow process.

Jeries et al. [8] analyzed sixteen types of polycyclic aromatic hydrocarbons (PAHs) from samples of raw and treated wastewater, sediments, sludge and plants growing nearby wastewater ways in Karak (Jordan). They have found that the highest concentration of PAHs was in the sludge. Most of the PAHs identified in sludge were of 4,5 and 6 rings as they are less soluble in water and consequently adsorbed to the sludge.

Suleiman et al. [6] conducted a survey to assess the current management practices, and volume of biosolids generated by wastewater treatment plants in Jordan. The study indicated that all wastewater treatment plants use solar drying beds and /or thickening of sludge/biosolids before being either disposed to landfills or stored on site. The annual cost of hauling the biosolids to landfill was estimated to be approximately one million US $. However, recently some new plants like new Samra and Shallala wastewater treatment plants are adopting anaerobic digestion of the sludge to produce biogas that is utilized in electricity production.

Batarseh [9] discussed the occurrence of some priority pollutants and the associated environmental risks for reclaimed water and sewage sludge reuse on agricultural land. Obstacles and limitations facing the wastewater reuse and sludge utilization in Jordan in terms of persistent organic pollutants were highlighted.

Egan [10] reviewed literature on the environmental and health risks associated with land application of biosolids. Furthermore, the study evaluated different methods and technologies for recovering energy from biosolids. The investigator concluded that biosolids can be considered as a renewable energy source. The use of biosolids for energy production is a more sustainable management strategy than land application.

Ranking of sludge management strategies by means of decision support systems was investigated by Bertanza et al. [11]. By using both worksheet model developed by the investigator and a commercially available decision support D-Sight, four sludge management alternatives were evaluated, namely, agricultural use, incineration, wet oxidation and energy recovery in cement kiln. The ranking process revealed that the highest preference is for agricultural use, followed by incineration and finally cement kiln and wet oxidation that has approximately the same preference.

By reviewing sewage sludge disposal strategies in terms of environmental sustainability and by using decision making tool like end of waste criteria and life cycle assessment, Kacprzak et al. [2] concluded that sewage sludge management strategy should focus on technologies that lead to product recovery that have potential to be marketed.

To determine sustainability sequence of the alternative technologies for the treatment of urban sewage sludge Ren et al. [1] employed three multi criteria decision making methods (MCDM) including the sum weighted method, digraph model, and TOPSIS. The researchers studied three treatment technologies, namely landfilling, composting, and drying incineration. They concluded that sustainability priority sequence was landfilling, drying incineration and composting in the descending order.

Garrido et al. [12] assessed five sludge treatment alternatives using environmental decision support systems. The alternatives covered in the study were anaerobic digestion, composting, incineration, gasification and supercritical water oxidation.

Gomez-Lopes et al. [13] has demonstrated the use of multicriteria decision support using TOPSIS method to select the disinfection technique for wastewater before being reused. The researchers found that based on the large weight given to cost and environmental criteria, the best disinfecting alternative was chlorination with 4 ppm, when the treated water to be reused for urban and agricultural purposes.

Comas et al. [14] tackled the issue of selecting wastewater treatment technology for small communities in Catalonia by developing a Knowledge-Based Decision Support System (KB-DSS) that is based on consultation of different knowledge sources. The developed KB-DSS system was applied to 3482 small scale water treatment plants in Catalonia. Castillo et al. [15] validated Novedar Environmental Decision Support System (EDSS) and demonstrated its capabilities by applying it to four real projects. The researchers concluded that the tested EDSS provides a useful tool to make decision on the right wastewater treatment process in the pre-design stage. The intuitionistic fuzzy AHP (IFAHP) method was used to select the optimal paradigm of mangroves for treating municipal wastewater [16]. The study showed that natural mangroves are the optimal alternative under most considered scenarios.

Most of the literature reviewed concluding that the selection of wastewater treatment technology is not an easy task [14,15] as we are dealing with a complex and semi-structured problem, where decision support system could be useful in such cases [11–17].

The main objective of this research is to develop a generic multi-criteria decision support system in order to assess and prioritize various sludge management alternatives in Jordan. The analytic hierarchy process (AHP) based modeling framework to support the decision related to prioritization process of sludge management option has been utilized. The criteria that were adopted for evaluation are based on technical, socio-economic, environmental and health risk aspects.

1.1. Importance of the study

The current practices of sludge management in Jordan that follow drying beds and disposal into solid waste disposal sites are neither environmentally friendly nor economically feasible, as they pose a high risk for polluting both ground and surface waters. In a country like Jordan, which suffers from chronic water shortage and considers the third poorest water country worldwide. It is important to protect water resources from such polluting practices of sludge disposal. Therefore, there is a pressing need to select a sludge management option that meets sustainability requirements through minimizing the potential risk of the country's scarce water resources. This can be considered as an added value of developing such a model that is applied for the first time in Jordan to tackle an important issue like sludge management. Furthermore, the study integrated various aspects of environmental and public health, technical and socioeconomic aspects in a comprehensive manner, which is not the case with most previous studies [17].

2. Production and utilization of the sludge from wastewater treatment in Jordan

In Jordan, there are currently 31 plants treating municipal wastewater. Fig. 1 shows the location of the treatment plants in various governorates of the country. The capacity and the treatment technology adopted by each plant are listed in Table 1 (WAJ). As it can be seen from the table, various treatment technologies are adopted by the plants with activated sludge treatment process being the most dominant one.

The amount of the sludge produced at each treatment plant and the current sludge management technology are listed in Table 2 [18]. It can be observed that the amount of sludge varies with the treatment plant capacity. The most widely management option is the drying bed. The average estimated total biosolids generated by the treatment plants in 2015 is 267.5 tons/d, while it is expected to reach in 2030 to about 350 tons/d.

To regulate the sludge use and disposal processes, in 2006 the Jordanian Government has issued a Technical Regulation (JS 1145/2006). This regulation put the guidelines that regulate the utilization of biosolids that are produced from the sludge of the wastewater treatment plants. The standard identified the quality characteristics of the produced biosolids so as to be used as organic fertilizers or soil conditioners or to be disposed into the landfills. The standards covered the whole cycle of biosolids generation via transportation until the final destination of land application or disposal in landfills [18,19]. The standard went a step further by addressing the quantity and quality of the biosolids to be applied to the land and the crop types. Public health and environmental requirements were also considered by the standard, where proximity to water bodies and residential areas were identified.

Despite the existence of such standard that regulates the utilization of sludge, in 2009 and 2011 instructions were issued by the Ministries of Agriculture and Environment prohibited the utilization of biosolids from wastewater sludge in land application as fertilizers or soil conditioner [18].

3. Methodology

Analytical hierarchy process (AHP) developed by Saaty in the early 1970s, as a multi-dimensional, multilevel, and multi factorial decision support tool. The process prioritizes different alternatives to achieve a certain goal by catego-

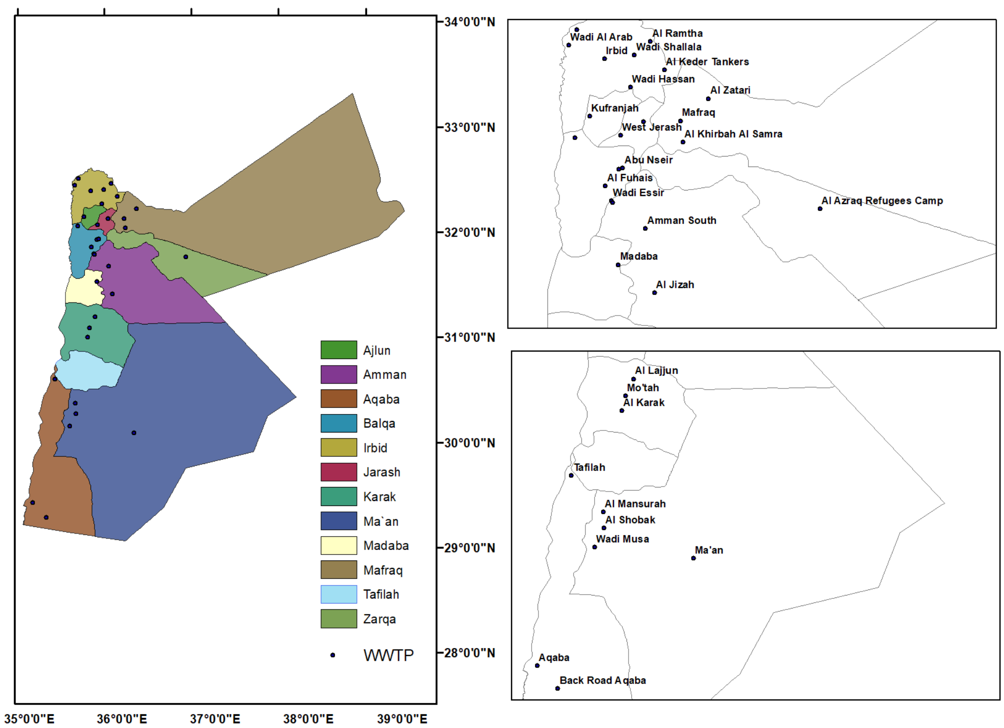

Fig. 1. Location of the wastewater treatment plants in different governorates of Jordan.

Table 1
List of wastewater treatment plants along with their design capacity and treatment technology [18]

Region	No.	Plant name	Inflow in 2015 m^3/d	Design capacity m^3/d	Treatment technology
Northern Region	1	Wadi Al Arab	10700	21000	AS
	2	Irbid Central	8600	11000	TF+AS
	3	Al Ramtha	4050	5400	AS
	4	Wadi Al Shallaleh	5000	13700	AS
	5	Wadi Hassan	1200	1600	AS
	6	Mafraq	3100	6550	AWSP
	7	Kufranja	2800	9000	AS
	8	Jerash	3300	3800	AS
	9	Al Merad	2300	9600	AS
	10	North Shuneh (Tanker)		1200	AS
	11	AL Ekeder (Tanker)	3232	4000	WSP
Central Region	12	As Samra	267000	315000	AS
	13	Al Baqaa	11700	14900	TF
	14	Abu Nusair	2300	4000	AS
	15	As Salt	6500	7700	AS
	16	Fuhais	2300	2400	AS
	18	Wadi Elseir	3800	4000	AWSP
	19	Al Jiza	624	To be decommissioned	
	20	South Amman	-	52000	AS
	21	Madaba	5600	7600	AS
Southern Region	22	Al Karak	1800	5500	TF
	23	Muta	5000	7100	AS
	24	Al Tafila	1600	7500	AS
	25	Ma'an	2400	3900	AS
	26	Wadi Musa	2500	3400	AS
	27	Aqaba Natural	7220	9000	WSP
	28	Aqaba Mechanical	15700	21000	AS
	29	Al-Lajun (Tankers)	735	1000	WSP
	30	Al Mansoura (Tankers)	13	50	WSP
	31	Tal Al Mantah (Tankers)	365	400	AS

AS = activated sludge TF = trickling filter AWSP = aerated waste stabilization ponds WSP = waste stabilization ponds.

rizing them under different categories and subcategories. After categorization, a pairwise comparison of attributes is performed based on informed judgment through soliciting experts' opinion. It is mathematically more rigorous form of the scoring method, providing a logical framework to determine benefit of each alternative [20].

To achieve the objectives of the study, the methodology that was followed is outlined below:

1. A comprehensive literature survey both computer and text based was carried out, so as to stand on the progress so far achieved in sludge management in general and particularly in the area of sludge management ranking and prioritization by applying decision support systems.
2. Collecting data on wastewater treatment plants in Jordan and detailed information on the sludge amounts generated on each plant and the methods of sludge management.
3. Construction of the AHP hierarchy which is composed of different levels related to the following:
   i. goal that has to be achieved, (selection of the optimal sludge management alternative),
   ii. the criteria based on which the evaluation was carried out, which included three criteria, namely environmental and public health, technical and socio-economic.
   iii. each of the three main criteria has three sub criteria which are dealing with specific aspect of the problem
   iv. finally, the management alternatives that are considered in the comparison
4. The problem hierarchy is presented in Fig. 2, which shows 3 criteria, 9 sub criteria and 5 alternatives that should be subjected for pair wise comparison. After the construction of the problem hierarchy, the pairwise comparison between the criteria as well as the

Table 2
Amounts of biosolids generated at each treatment plant and methods of sludge pretreatment [18]

Region	No.	Plant name	Biosolids in 2015 (kg/d) dry solids	Projected biosolids in 2030 (kg/d) dry solids	Sludge management option at the plant
Northern Region	1	Wadi Al Arab	9,237	12,771	DB, CEN
	2	Irbid Central	6,010	7,405	DB
	3	Al Ramtha	7,245	9,127	DB
	4	Wadi Al Shallaleh	8,045	9,842	DB, SP
	5	Wadi Hassan	3,468	4,661	DB,SP
	6	Mafraq	2,248	2,790	DB
	7	Kufranja	3,591	4,145	DB, SP
	8	Jerash	4,014	5,160	–
	9	Al Merad	3,845	4,944	DB. CEN
	10	North Shuneh (Tanker)	2,634	3127	DB
	11	AL Ekeder (Tanker)	–	–	–
Central Region	12	As Samra	147,000	194,000	BFP, DB
	13	Al Baqaa	11,931	14,317	–
	14	Abu Nusair	2,042	3,153	–
	15	As Salt	3,494	4,274	DB
	16	Fuhais	1,723	2,285	DB
	18	Wadi Elseir	1,460	1,830	–
	19	Al Jiza		–	
	20	South Amman	22,811	32,041	DB
	21	Madaba	4,631	5,629	DB,SP
Southern Region	22	Al Karak	2,743	5,061	DB
	23	Muta	2,449	3,097	DB
	24	Al Tafila	1,871	3,264	–
	25	Ma'an	2,316	2,672	DB
	26	Wadi Musa	687	776	–
	27	Aqaba Natural	369	411	–
	28	Aqaba Mechanical	5,118	6,176	DB
	29	Allajun (Tankers)	4,361	4,689	–
	30	Al Mansoura (Tankers)	41	46	–
	31	Tal Al Mantah (Tankers)	2,181	2,327	DB, SP

DB = drying bed SP = screw press CEN = centrifuge BFP = belt filter press.

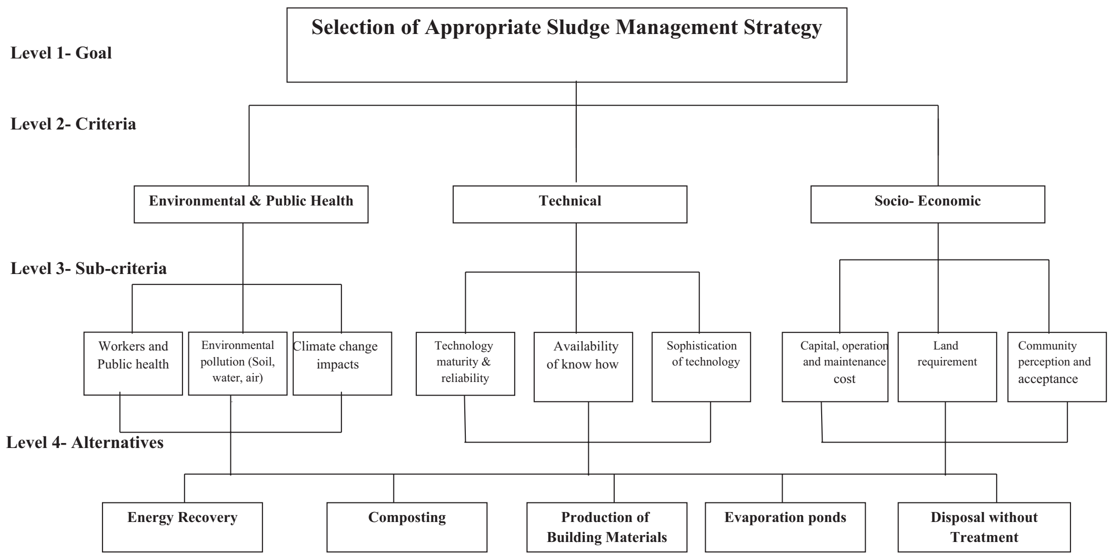

Fig. 2. Analytical hierarchy model for the selection of sludge management strategy.

subcriteria at each level has been performed. As a result of the comparison, matrices of judgments were generated. The weights of judgment in the matrices are based on soliciting experts' opinions. Stakeholders with different backgrounds were consulted which included environmentalists, researchers, plants operators, public figures and policy makers. Table 3 shows the categories of stakeholders whose opinions were solicited and the number from each category.

5. Generate a priority vector for the judgments matrices by normalizing the values in the matrices.
6. Consistency analysis was carried out for each criteria judgment by calculating consistency index (CI) and consistency ratio (CR). Considering the randomness in judgment the consistency ratio may be calculated as follows:

$$CR = CI/RI$$

where RI the random index which expresses the expected value of the CI corresponding to the order of matrices.

In case where the CR value is within acceptable range (Usually less than 10%), the judgments are considered consistent. Otherwise, the procedure will be repeated till the CR values will lie within the desired range.

Synthesize the judgments by aggregating the weights through hierarchy to determine the composite priorities of each sludge management alternatives.

3.1. Alternatives for sludge management system

Five alternatives of sludge management processes were considered in the study, namely, energy recovery, composting, production of building materials, evaporation ponds, and disposal without treatment (Fig. 2). These alternatives were selected as it is believed that they are the most suitable for Jordanian local circumstances.

3.1.1. Energy recovery

Wastewater sludge produced by municipal wastewater treatment processes contains organic matter that has energy content. This energy can be recovered by different means and methods [21]. Anaerobic digestion (AD) is among those methods where consortium of microorganisms (mainly bacteria) degrading the organic fraction of the sludge under anaerobic conditions methods to produce biogas that is mainly consist of methane. Using the produced methane from AD process in combined heat and power (CHP), it is possible to generate 1.25–2 kWh of electricity from each cubic meter of sludge [22].

Sludge incineration is another option of sludge management. It is possible by incinerating the sludge to recover energy, however the harmful emissions that may produce from the incineration process like heavy metals content requires further treatment that is reflected on the treatment cost [21]. In general, the thermal process of sludge treatment are suffering from the low heating value of the sludge (less than 15 MJ per kg of dry solids) and high moisture content even after dewatering (70–90%). [21].

Currently in Jordan, there are two wastewater treatment plants adopting sludge AD. Those are Alsamra and Shallala wastewater treatment plants, where the generated biogas is being used for heat and power generation that are utilized in plant operations.

3.1.2. Composting

Composting is a biological aerobic process during which the biodegradable fraction of the organic matter available in the sludge (biosolids) is decomposed by a variety of microorganisms which utilizes organic matter as a carbon source to produce a humus like material that can be utilized as a fertilizer or soil conditioner. The quality of the produced compost is of great importance, as it will affect the soil characteristics. In general the compost quality characteristics depend on the conditions under which composting operation takes place and to which extent the biodegradation process proceeded [23,24]. Sludge composting is a viable option for sludge management in Jordan as it proved success in producing compost complying with EPA standards. However, sludge should be dewatered before composting, and the process requires considerable land space [7].

As mentioned earlier, despite the existence of technical regulation (JS 1145/2006) that regulates the use of sludge as a fertilizer (for fodder and fruit trees) or soil conditioner (for rangeland) and despite the fact that most of the country soil lacking nutrients, the composting of biosolids in Jordan is not applied. This is due to the objections of the Ministries of Agriculture and Environment that prohibited the use of biosolids for the purpose of fertilizers and soil conditioners production [18].

3.1.3. Production of building material

Recently, several research works have been published on the suitability of sewage sludge utilization in the production of building materials. Krishna et al. [25] investigated the possibility of using the dewatered sewage sludge in producing bricks. Johnson et al. [26] have reviewed the potential use of sewage sludge in construction industry. They reported the use of waste sludge in brick manufacturing, as artificial aggregate, as cement like material, as well as in concrete and ceramic production. The building materials produced however, may pose a risk to public health and

Table 3
List of stakeholder categories and their numbers whose opinions were solicited during the study

No.	Stakeholders category	Profession	Number
1.	Environmental academicians	Lecturers and researchers	4
2.	Wastewater professionals	Policy makers and plant operators	3
3.	Community members	Residents and NGOs members	3
	Total		10

environment, as the sludge contain pathogens and heavy metals that may leach from the materials during the building process or after putting the buildings in use. Up to the investigator knowledge, in Jordan till now utilizing sludge in building materials is not practiced on a reasonable scale.

3.1.4. Evaporation ponds

One of the simplest alternatives to manage the sludge is to store it in an open pond where it will be subjected to evaporation. Evaporation ponds are used to evaporate sludge utilizing solar energy. Drying beds is one alternative of sludge drying, where the sludge is exposed to solar drying usually in open air. Most wastewater treatment plants in Jordan using drying beds [18]. In many cases evaporation from ponds is associated with emission potential of volatile organic and odorous compounds.

3.1.5. Disposal without treatment

Sludge disposal without treatment may take several forms. It may be simply disposed into the sea or into nearby water course, when the treatment plant is located close to the seashore or river bank. Alternatively, it may be transported by tankers to the nearby landfill. In any case, such practices pose high risks to the environment and public health. From economic point of view, it is less costly than other alternatives.

3.2. Selection criteria for appropriate sludge management systems

To select the proper alternative of sludge management, several criteria (attributes) were considered. The final criteria used in the assessment process was used based on their comprehensiveness and robustness. As it can be seen from Fig. 2, four criteria were selected which were broken down further into sub criteria. The Environmental criteria subcategories are:

Workers and public health, where the risks on the health of labor working in a facility and health of people who are directly affected from living close to the treatment facility are considered.

Environmental pollution (water, soil and air) considers the potential impact of the selected treatment technology on the ecosystem and environmental elements like both surface and groundwater as well as the soli and the air are considered under this subcategory.

Climate change, where the carbon foot print of the selected technology and the associated emissions of greenhouse gases is considered under this subcategory.

On the other hand, the technical criteria have three subcategories as follows:

Technology maturity and reliability, which refers to widespread and readiness of sludge management technology to operate under different operational conditions for long enough time without faults and problems. Knowing the number of full scale facilities in operation which utilize such technology is important information in this case.

Availability of knowhow, which considers the existence of practical knowledge and skills regarding running and maintaining the selected sludge management technology in an efficient and effective way.

Sophistication of technology, which refers to high and advanced technology that may be applied in the sludge management. Such technologies require skillful human resources and spare parts that may be not available in developing countries. The ease of integrating the proposed sludge process with the existing wastewater treatment facilities is another issue to be considered.

Finally, the socio-economic category includes the following subcategories:

Capital, operation and maintenance cost, where the initial investment (CAPEX) associated with the selected sludge management processes as well as, the running and maintenance costs (OPEX) like spare parts, power consumption, and salaries are considered.

Land requirement, which considers the area of the land that will be occupied by the selected sludge management process. In certain countries the land availability is limited, while in others huge undeveloped areas are available and can be utilized for constructing the treatment facility.

Public perception and acceptance, public opinion is an important factor that should be considered in the selection of sludge management option. Furthermore, public perceptions and Not in My Back Yard Syndrome (NIMBY) should be taken into account, as people do not prefer to have waste treatment facilities nearby their neighborhoods.

4. Results and discussion

Selecting a suitable and attractive wastewater sludge management option is an important step in sustainable wastewater treatment. Although literature covered various management options and strategies, little is known about relative importance of each strategy. Considering the selection of sludge management option as a multicriteria decision making problem, the relative importance of each strategy can be effectively obtained using AHP approach.

4.1. Pairwise comparison

The pair-wise comparison between the criteria as well as the sub criteria at each level of the hierarchy towards achieving the goal of selecting the optimal sludge management option has been performed. Fig. 3 presents the calcu-

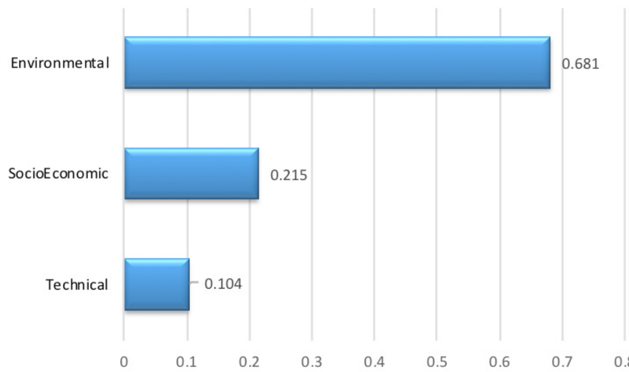

Fig. 3. Weights of the sludge management alternative.

lated weights of each of the three selection criteria using Expert Choice Software. It can be observed that the environmental criteria have the highest weight of 0.681 which is the most important criteria in selecting the sludge management strategy, followed by socio economic criteria with a weight of 0.215. The technical criteria appear to be the least important one with a weight of 0.104. This implies that when selecting a sludge management option, the environmental criteria should have the highest priority.

Under the environmental criteria, the analysis revealed those workers' and public health sub criteria has the highest priority with 0.54 weight, followed by environmental pollution of soil water and atmosphere with a weight of 0.29 and the least priority was given to climate change of 0.17, as illustrated in Fig. 4.

The sub criteria weight analysis of the socio-economic criteria is presented in Fig. 5. It can be observed that the high rank has given to capital, operation and maintenance cost with a weight of 0.497, followed by community perception index with a weight of 0.312 and finally land requirement with 0.191. In a developing country like Jordan, the cost is an important factor which is reflected in the results of the analysis by giving cost the highest weight. However, because in Jordan, there is a plenty of vacant arid land, the land requirement has lower priority and was given the lowest weight.

As for the technical criteria, the sub criteria weight analysis is illustrated in Fig. 6. It can be seen, both the sophistication of technology and technology maturity and reliability having approximately the same weight, while the availability of know how has lowest weight.

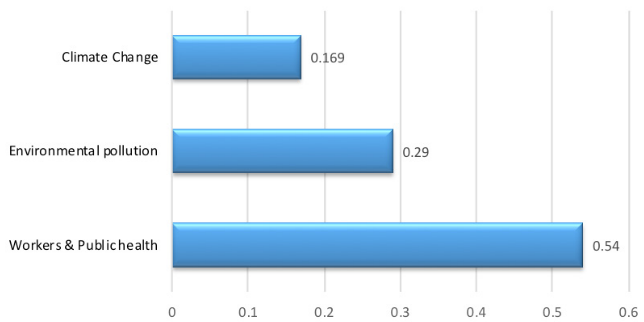

Fig. 4. Calculated weights of the sub criteria under environmental criteria.

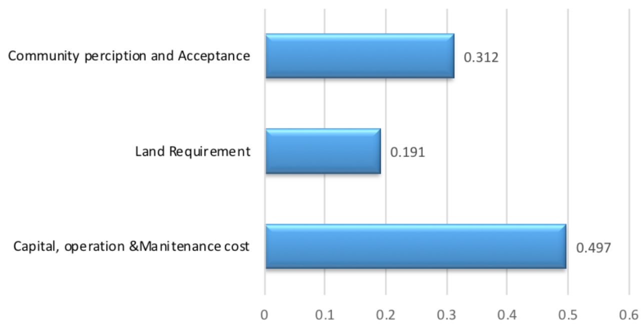

Fig. 5. Calculated weights of the sub criteria under Socio-economic criteria.

The prioritization results of the sludge management alternatives under all criteria are presented in Fig. 7. The comparison shows that the energy recovery is the most preferred option with a weight of 0.380, followed by composting with a weight of 0.224. The disposal without treatment option ranks next with a weight of 0.178, followed by evaporation ponds with a weight of 0.127 and finally production of building materials option is the least preferred one with a weight of 0.091.

This is expected since Jordan is not an oil producing country and depends mainly on imported sources of energy, and hence the energy recovery option is the most preferred one. Composting also is the second preferred alternative for sludge management, which is also expected, as Jordanian lands are mainly arid and semi-arid areas (more than 90%). The regulatory barriers imposed by the Ministries of Agriculture and Environment that bands the utilization of compost from sludge and biosolids renders the compost option less attractive than energy recovery, while in Italy for example, the most preferred option is to use sludge for agriculture [11]. When considering the use in building materials production, it has the lowest priority. This is may be due to the environmental and public health risks that are associated with such practices. It should be emphasized here that there is no universal ranking for the sludge management that suits every country. The local circumstances should be considered when selecting the appropriate management option [4].

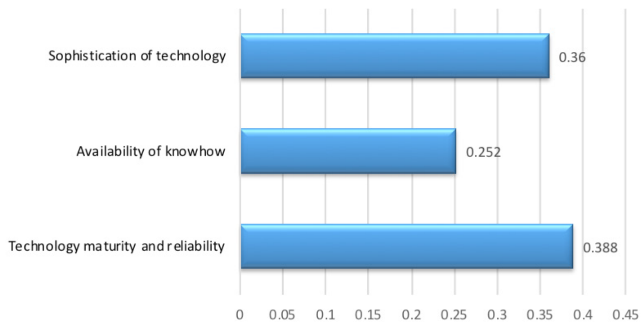

Fig. 6. Calculated weights of the sub criteria under technical criteria.

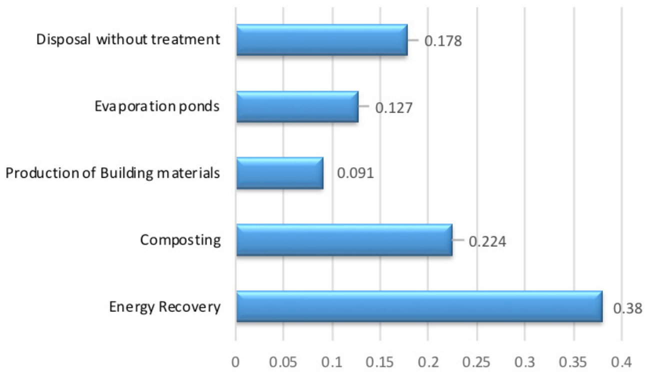

Fig. 7. Priority weights of different sludge management alternatives under all criteria to achieve the goal.

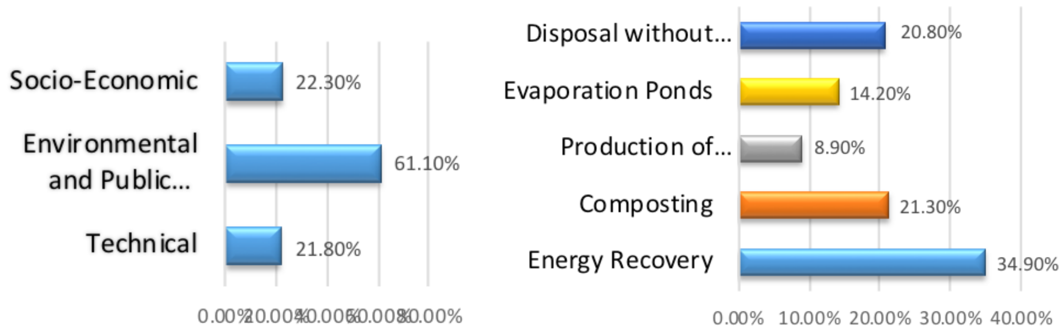

Fig. 8. Sensitivity of sludge management alternatives as a result of decreasing the weight of the environmental criteria by 7%.

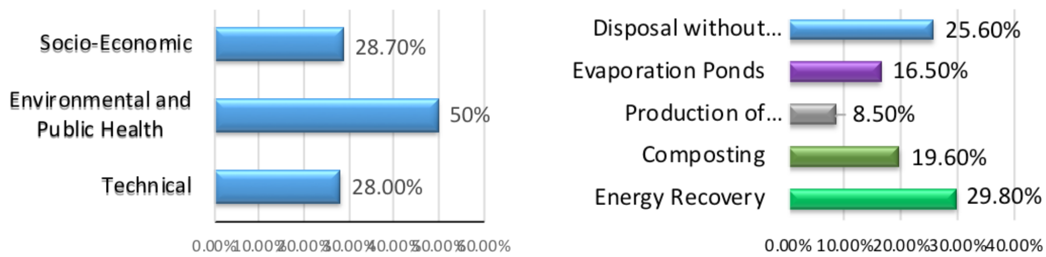

Fig. 9. Sensitivity of sludge management alternatives as a result of decreasing the weight of the environmental criteria by 18%.

4.2. Sensitivity analysis

The sensitivity of the wastewater sludge management options due to changes in priorities of the criteria is an important factor that can give an idea about the impact of each criterion on the selected alternative. To investigate that, sensitivity analysis was carried out based on what if scenarios. Dynamic sensitivity graphs were developed to determine how the overall result will change when the priorities of the criteria change. The dynamic sensitivity analysis is illustrated in Fig. 8. The weights selected in the analysis were those that could affect sensitivity of the alternatives. For example, it can be seen that by reducing the weight of the environmental criteria from 68.1% to 61.1%, the ranking of alternatives is still the same. However, the alternatives weights have changed.

The change in rankings and weights starts only after decreasing the weight of environmental criteria down to 50.1%, where the energy recovery alternative still ranking first but with its weight being decreased by 8.2% (from 38% to 29.8%), while the second rank is being taken by disposal without treatment alternative instead of composting with increase of its weight by 7.8% and the weight of composting and production of building materials decreased by 2.8%, 0.6%, respectively (Fig. 9).

5. Conclusions and recommendations

The management of sewage sludge generated in wastewater treatment plants is a challenging and hot issue. This problem has a lot of associated costs at an economical level, but also poses risks on the public health and the ecosystems. Therefore, the best practices nowadays to deal with sludge as a resource not as a liability.

In this study AHP has been used as a tool to assess in selecting sludge management strategy. A four level model was developed, which proved to be a useful tool in prioritizing the evaluation criteria, as well as selecting the appropriate sludge management option that suits the local Jordanian circumstances. Energy recovery option appeared to be the option of choice under the multi criteria evaluation. The model provides the decision makers with a useful tool when thinking of selecting the right sludge management option.

Further studies should be conducted that consider other alternatives of sludge management options. In addition, market study analysis should be carried out for the alternatives under consideration.

Acknowledgement

The author is grateful for the financial support provided by the Deanship of Scientific Research at Jordan University of Science and Technology to conduct the current research during his sabbatical leave that was spent at Yarmouk University (Jordan).

References

[1] J. Ren, H. Liang, F.T.S. Chan, Urban sewage sludge, sustainability, and transition for eco-city: multi-criteria sustainability assessment of technologies based on best-worst method, Technol. Forecast. Social Change, 116 (2017) 29–39.

[2] M. Kacprzak, E.Neczaj, K. Fijałkowski, A. Grobelak, A. Grosser, M. Worwag, A.Rorat H. Brattebo, A. Almas, B.R. Singh, Sewage sludge disposal strategies for sustainable development, Environ. Res., 156 (2017) 39–46.

[3] O. Nowak, Optimizing the use of sludge treatment facilities at municipal wastewater treatment plants, J. Environ. Sci. Health Part A, 41 (2006) 1807–1817.
[4] G. Barberio, L. Cutaia, V. Librici, Treatment and disposal of sewage sludge: comparative life cycle assessment on Italian case study, Environ. Eng. Manage. J., 12 (2013) 7–10.
[5] A.H. Tamimi, C.P Gerba, B. Hayek, C.Y. Choi, R. J Freitas, Characterization of the quality of drying bed treated biosolids in Jordan, J. Resid. Sci. Technol., 4 (2007)109–115.
[6] W. Sulieman, C.P. Gerba, A.H. Tamimi, A. Al Sheraideh, B. Hayek, Management practices of sludge and biosolids treatment and disposal in Jordan, J. Resid. Sci. Technol., 7 (2010) 63–67.
[7] O. Hassouneh, A. Jamrah, K. Qaisi, Sludge stabilization by composting: a Jordanian case study, Bioprocess Eng., 20 (1999) 413–421.
[8] A. Jiries, H. Hussain, J. Linetelmann, Determination of polycyclic aromatic hydrocarbons in wastewater, sediments, sludge and plants in Karak Province, Jordan, Water Air Soil Pollut., 121 (2000) 217–228.
[9] M. Batarseh, Sustainable use of wastewater and sludge in Jordan: Residues of persistent organic pollutants: A Review, Advanced Water Supply and Wastewater Treatment: A Road to Safer Society and Environment, P. Halvinek et al., eds., Springer Science Media, 2011, pp. 219–226.
[10] M. Egan, Biosolids management strategies: an evaluation of energy production an alternative to land application, Environ. Sci. Pollut. Res., 20 (2013) 4299–4310.
[11] G. Bertanza, P. Baroni, M. Canato, Ranking sewage sludge management strategies by means of decision support systems: a case study, Resour. Conserv. Recycl., 110 (2016) 1–15.
[12] M. Garrido-Baserba, M. Molinos-Senante, J.M. Abelleira-Pereira, M. Fades-Guelfo, L.A. Poch, F. Hernandez-Sancho, Selecting sewage sludge treatment alternatives in modern wastewater treatment plants using environmental decision support systems, J. Cleaner Prod., 107 (2015) 410–419.
[13] M.D. Gomez-Lopez, J. Bayo, M.S. Garcip-Cascales, J.M. Angosto, Decision support in disinfection technologies for treated wastewater reuse, J. Cleaner Prod., 17 (2009) 1504–1511.
[14] J. Comas, M. Alemany, M. Poch, A. Torrens, M. Salgot, J. Bou, Development of a knowledge-based decision support system for identifying adequate wastewater treatment for small communities, Water Sci. Technol., 48 (2003) 393–400
[15] A. Castillo, J. Porro, M. Garrido-Basbera, D. Ross, D. Renzi, F. Fatone, D. Gomez, M. Poch, Validation of a decision support tool for wastewater treatment selection, J. Environ. Manage., 184 (2016) 409–418.
[16] X. Ouyang, F. Guo, Intuitionistic fuzzy analytical hierarchical processes for selecting the paradigms of mangroves in municipal wastewater treatment, Chemosphere, 197 (2018) 634–642.
[17] X. Ouyang, F. Guo, D. Shan, H. Yu, J. Wang, Development of the integrated fuzzy analytical hierarchy process with multidimensional scaling in selection of natural wastewater treatment alternatives, Ecol. Eng., 74 (2015) 438–447.
[18] USAI, Water Reuse and Environmental Conservation Project Kingdom-Wide Biosolids Management Strategy July 2014. Prepared By AECOM.
[19] A.H. Tamimi, R.J. Freitas, W. Suleiman, Developing a manual for management of sludge and biosolids at Jordanian wastewater treatment plants, technical report prepared for the sustainable development of dry lands project, the Jordan component international arid lands consortium, the university of Arizona, 2010.
[20] L. Pecchia, P.A. Bath, N. Pendelton, M. Bracle, Analytical hierarchy process (AHP) for examining healthcare professionals' assessments of risk factors, Inf. Med., 50 (2011) 435–444.
[21] K. Dussan, R. Monghan, Integrated thermal conversion and anaerobic digestion for sludge management in wastewater treatment plants, Waste Biomass Valor., 9 (2018) 65–85.
[22] V. Mema, P. Hlabela, S. Marx, Assessing electric power potential of municipal wastewater sludge, J. Clean Energy Technol., 5 (2017) 60–63.
[23] M.F. Hamoda, H. Abu Qdais, J. Newham, Evaluation of municipal solid waste composting kinetics, Resour. Conserv. Recycl., 23 (1998) 209–223.
[24] H. Abu Qdais, M. Al-Widyan, Evaluating composting and co-composting kinetics of various agro-industrial wastes, Int. J. Recycl. Organ. Waste Agricult., 5 (2016) 273–280.
[25] P.N. Krishna, J.M. Vivek, K. Shibu, Suitability of sludge as a building material, Int. J. Scient. Eng. Res., 4 (2013) 23–28.
[26] O.A. Johnson, M. Napiah, I. Kamaruddin, Potential uses of waste sludge in construction industry: a review, Res. J. Appl. Sci. Eng. Technol., 8 (2014) 565–570.