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Feasibility of anaerobic digestion as an option for biodegradable and sewage sludge waste management in the Kingdom of Bahrain

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ABSTRACT

Solid waste management (SWM) represents a main challenge to the developing countries. Almost all of the solid waste in these countries are dumped into landfills, which harms the environment, public health, as well as affecting the economy and society. Dumping of biodegradable waste including sewage sludge resulted from wastewater treatment plants into the landfill results in methane emission, which is a greenhouse gas 25 times more potent than carbon dioxide. Thus, finding a sustainable solution to manage the biodegradable and sewage sludge waste tend to be crucial. This study aims to explore the feasibility of anaerobic digestion (AD) technology to manage the biodegradable and sewage sludge waste in the Kingdom of Bahrain. AD is an important waste-to-energy technology that leads to produces biogas, an important and promising renewable energy resource for the country. Cost-benefit analysis (CBA) was used in this study that shows the feasibility of the AD project. In addition, the contribution in reduction of the landfill methane emission was estimated. The study may provide sufficient information for future adoption of evidence-based technology selection in order to adopt SWM technologies in Bahrain, which contributes to the decision and policy-making processes.

Keywords: Biodegradable waste management; Sewage sludge; Anaerobic digestion; Kingdom of Bahrain

1. Introduction

Municipal solid waste (MSW) generation rises steeply with the increase in population growth rate, developmental activities, economic and industrial development and urban growth. It has become a globally addressed issue [1,2]. If it is not managed properly, negative consequences will appear and affect the public health, environment and economy [3,4]. In developing Asian countries, the organic waste represents the majority of municipal solid waste which it is disposed in landfills. As a result, it degrades in anaerobic conditions and generates landfill methane, the greenhouse gas that is 25 times more potent than CO_2. Accordingly, biodegradable waste represents a promising resource that can be used to produce bio-energy as well as soil fertilizer. On the other hand, the sewage sludge resulted from wastewater treatment plants is also dumped into the landfill, which is considered a main part of the biodegradable waste. Thus, sustainable management of this waste can significantly contribute to climate change mitigation [5–7]. With regard to greenhouse gas (GHG), organic household waste has contributed the most to the emissions from various types of waste. In most developing countries where the organic content of waste is high, improper management of waste (e.g., open dumping and landfill of organic waste without gas recovery and open burning of plastic waste) may lead to higher GHG emissions in the future [8].

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2. Waste management in the GCC countries

Waste generating per capita ranked among the highest in the world in the Gulf Cooperation Council (GCC) countries [4]. The estimated total amount of waste generated in the GCC countries range from 90 million to 150 million metric tonnes annually, with the UAE being the highest generator at approximately 2.2 kg per capita daily. The amount of recycled waste is around 5% of the total, with the rest being accounted for landfills or, even worse, to illegal dump sites. The amount of waste generated is expected to grow rapidly to anywhere between 1.5 and 2 times of the current volume in 2021. Changes in consumption patterns of the GCC countries, have led to an increase in the MSW dumping. Al-Ansari [2] and MWMUPA [8] have argued that waste management protocols need to be re-evaluated in order to establish methods that contribute to minimizing greenhouse gas emissions, improving the efficiency of resource management, and designing more eco-friendly management plans in GCC countries. The composition of the waste would generally suggest that a large part of it is biodegradable. However, this is not reflected in common waste management practices in the GCC Countries, where most waste goes to landfill. In countries like Bahrain, Qatar, and the UAE, landfill space is running low and this practice is becoming a major problem.

3. SWM in the Kingdom of Bahrain

The Kingdom of Bahrain is located in the heart of the Arabian Gulf, west of the Asian Continent. It is an archipelago of 33 islands with Bahrain Island being the largest land mass which represents approximately 80% of the total land area of the Kingdom of Bahrain and amounts to 770 km^2. The Kingdom is split into four Governorates namely the Capital, Muharraq, Northern, and Southern Governorates. The Kingdom of Bahrain is one of the GCC countries. Oil and natural gas are the primary natural resources in Bahrain. The population growth rate is 7.4% on average.

Since organic waste is considered as the most harmful portion of the SW content due to its hazardous environmental impact, organic waste management becomes a concern in many of the developing countries with the highest organic portion within their MSW content. Waste composition is considered to be one of the main factors influencing emissions from solid waste treatment, as different types are known to contain varying amounts of degradable organic carbon (DOC), and fossil carbon.

3.1. Anaerobic digestion

Organic waste in landfills undergo degradation process, mainly anaerobic digestion, resulting in methane gas production, which is considered to be the most harmful GHG that causes global warming and as a consequence, climate change. The biodegradable waste (consisting of garden and green waste, papers and cardboards, food waste) represents the highest composition percentage in Bahraini domestic waste, according to MWMUPA [8]. It was above 60% in 2017, while it continues the average of 63% for 2018 and 2019, which shows that biodegradable waste continues to be one of the biggest components (percentage wise) of Bahrain's MSW.

Anaerobic digestion (AD) is a complex biochemical process for the treatment of organic waste, which occurs in a vessel in the absence of oxygen. In this process, breaking down of the organic material occurs by micro-organisms, which leads to the formation of mixture of carbon dioxide and methane gas known as "Biogas", which is typically used to provide electrical power generation, heat, and a solid and liquid digestate. The digestate quality is dependent on availability of source- segregated organic waste stream [8,9]. The relevance of biogas technology lies in the fact that it makes the best possible utilization of organic waste as a renewable clean energy source [8].

Anaerobic digestion of the organic fraction of municipal solid waste (OFMSW) is being widely utilized globally because this technology complies with the philosophy of sustainability. The energy recovered from anaerobic digestion of OFMSW is renewable and the effluent can be returned to the agricultural land, thus recovering the remaining organic matter and nutrients [10].

According to Appels et al. [11], energy from biomass and waste is one of the most dominant renewable energy sources to be used in future. It has been found that different types of biomass and waste are suitable for AD, including OFMSW, Waste oils, animal fats, crops and agricultural, manure and sludge.

Furthermore, AD technology strongly relies upon the input material. Therefore, it is crucial that the waste is separated before the treatment. Materials such as plastics will reduce process' efficiency [12]. This is consistent with the views of the American Biogas Council as per which pre-sorting is necessary to prevent clogging of the pumps and to reduce the amount of reactor volume occupied by inert material. Even source-separated waste inevitably contains metal and plastic contaminants and hence, must be pre-sorted.

The biogas produced by anaerobic digestion primarily comprises of (CH_4 ≈ 60% by volume), carbon dioxide (CO_2 ≈ 40% by volume), and small traces of hydrogen sulphide (H_2S), hydrogen (H_2), nitrogen (N_2), carbon monoxide (CO), oxygen (O_2), water vapour (H_2O) or other gases as well as vapors of various organic compounds [13]. According to the American Biogas Council, many different anaerobic digester systems are commercially available based on organic waste stream type (manure, municipal wastewater treatment, industrial wastewater treatment and municipal solid waste). Anaerobic digestion of the organic fraction of MSW provides an engineered and highly controlled process of capturing methane. It is claimed that the current trend is toward anaerobic digestion of source separated from organic waste streams, including food waste, yard trimmings and soiled paper. Therefore, segregation at source is a main enabler to AD adoption in large scale SWM [8,15].

The number of plants treating the digestible fraction of household waste in Europe grew from three biogas plants in 1990 to 195 in 2010, with a total capacity of 5.9 million tonnes, with a predicted expansion of current capacity every 5 y [16]. In 2010, about 3% of the organic fraction of municipal solid waste produced in Europe was treated by the AD, representing 20%–30% of the biological treatment capacity of organic wastes from households

(Al Seadi et al. [16]). Analogously, (McKendry [17]) claimed that AD is a commercially proven technology and is widely used to treat high moisture content organic wastes that may reach 80%–90% moisture.

American Biogas Council [14] has specified the anaerobic digestion systems for MSW, which include:

(1) *Single-stage wet digesters*: Typically simpler to design, build, and operate and generally less expensive, the organic loading rate (OLR) of single-stage digesters is impeded by the ability of methanogenic organisms to tolerate the sudden decline in pH resulting from rapid acid production during hydrolysis.
(2) *Dry fermentation*: Type of single-stage digester, but distinctive from other AD categories because feedstock are in a solid state that can be handled using a front-end loader; normally, no additional water is added. Digestion takes place at 20%–45% total solids, and can be done in either a batch or continuous mode. In the batch mode, materials are loaded into chambers before being inoculated and maintained until the end of the retention time. In continuous mode, fresh feedstock is continuously fed to the digester and the digestate is continuously removed.
(3) *Two-stage digesters*: System separates the initial hydrolysis and acid-producing fermentation from methanogenesis, which enables higher loading rates for high nitrogen containing materials but requires additional reactors and handling systems. Another important design parameter is the total solids (TS) concentration in the reactor, which is expressed as a fraction of the wet mass of the prepared feedstock. The remainder of the wet mass is water by definition. Feedstock is typically diluted with process water in order to achieve the desirable solids content during the preparation stages.

Moreover, Cioabla et al. [9] outlined the factors affecting the performances of an anaerobic digester. They claimed that these factors can be divided into three main classes: (i) feedstock characteristics, (ii) reactor design and (iii) operational conditions. Among the operational conditions, temperature and pH are found to be important parameters.

Kang and Yuan [18] have stated the conditions required for a successful AD. They contended that moisture content is considered as one of the most important factors affecting the waste stabilization which play an important role in:

(1) Controlling cell turgidity;
(2) Reacting in polymer hydrolysis;
(3) Solubilizing and transporting nutrients, intermediates, products, inhibitors, enzymes, and microorganisms;
(4) Modifying the shapes of enzymes and other macromolecules;
(5) Exposing more of the waste surface to microbial attack.

Raising the moisture content of an anaerobic digester is known to increase the generation of methane. According to previous studies, the minimum moisture content is 36% for a mechanically mixed, mesophilic digester fed with the putrescible fraction of MSW. They mentioned three temperature ranges for AD process that is predicated on the bacteria type:

(1) cryophilic, less than 20°C (very slow, so rarely used for digestion of MSW);
(2) mesophilic, 20°C–45°C (35°C is generally used for mesophilic operation);
(3) thermophilic, above 45°C (55°C is generally used for thermophilic operation), digestion is faster in the thermophilic range.

According to American Biogas Council [14], captured biogas is transported via pipe from the digester, either directly to a gas use device, or to a gas treatment system (e.g., for moisture or hydrogen sulphide removal). According to them, high concentrations of sulphur lead to the formation of hydrogen sulphide in the digester, which cause the corrosion of the combustion device or other downstream equipment.

Meanwhile the chemical oxygen demand (COD) is a measure of the capacity of water to consume oxygen during the decomposition of organic matter and the oxidation of inorganic chemicals, such as ammonia and nitrite. On the other hand, biological oxygen demand (BOD) is a measure of the amount of biological substrate materials within a water or wastewater [19]. BOD is similar to the function of chemical oxygen demand (COD) in that both measure the number of organic compounds in water. The American Biogas Council has shown that the high chemical oxygen demand (COD) and solids loading make the feedstock well-suited for treatment using anaerobic processes. Hence, a high COD is required in order to achieve a successful AD process.

3.2. Feasibility of AD for Bahrain biodegradable waste

Abbas [15] empirically characterized the organic household waste in Bahrain and found that the moisture reached 73%, which is optimum for the AD process. According to Al Sabbagh et al. [4], the organic fraction of the MSW in Bahrain reached (60% wt.) and is comparable to that in middle- and low-income cities (50%–80% wt.). Since organic waste is considered as the most harmful portion of the MSW content due to its hazardous environmental impact, organic waste management becomes a concern in many of the developing countries with the highest organic portion within their MSW content. Waste composition is considered to be one of the main factors influencing emissions from solid waste treatment, as different types are known to contain varying amounts of degradable organic carbon (DOC), and fossil carbon.

According to the MWMUPA [8], the total waste going to Askar Landfill – the only landfill in Bahrain which already reached its limits- is about 2,131,683 ton, the details of waste composition are shown in Table 1. Accordingly, the total biodegradable waste in the landfill comes from: – Domestic waste (food, papers and cardboard, green), Garden waste, and Dead animals. – Commercial waste: Food, green, paper and cardboard. – Industrial waste: Food, green, paper and cardboard. – Sludge from wastewater treatment plant (WWTP). Based on the Waste Audit Report [8,20], the average of the last 2 y was considered in this study. Therefore, the percentages of the biodegradable fraction under each of the above categories were calculated and found to be as shown in Table 2, while Table 3 represents the total

Bahrain's biodegradable waste composition in ton per year in details.

4. Methodology: cost-benefit analysis (CBA)

CBA provides a means for systematically comparing the value of outcomes with the value of resources achieving the desired outcomes. It measures the economic efficiency of the proposed technology or project.

Hochman et al. [21] has evaluated four available waste treatment technologies: direct combustion, landfilling, composting, and anaerobic digestion in New Jersey – USA using the CBA method. Since the economic criterion is a priority worldwide among governments, this research took the economic feasibility into consideration as a main criterion for technology selection. Furthermore, Moutavtchi et al. [22] showed that CBA is useful for decision making in MSW management because it can be utilized as an efficient tool for information support for implementation of waste management technologies. Sadiq and Kaneesamkandi [23] claimed that it is necessary to predict the biogas yield and to perform cost analysis in order to investigate whether the waste conversion into biogas and digestate is financially feasible [15].

In order to commence the CBA for the AD technology project, the considered project period in this study was 15 y. Data in this section is based on the cost estimated from waste management technologies plants in developing countries ($/ton) in Germany [24]. Further Investigations done by the author through communications with experts of supplying companies in the industrial sector. AD technology has a fixed direct cost (capital cost), which includes the cost of: Consultant fees, environmental and social impact assessment (ESIA) and permits, equipment, engineering design and building. This cost is paid at the first year of the project. Next, the indirect costs that need monthly payment (operation and maintenance cost) include: land lease agreement, loan repayments, electricity, water, labour of maintenance, insurance, labour of operations and transportation. The benefit of AD technology is realized through two different ways: by sales estimated depending on the type of technology and product market price; and through the savings realized by stopping the dumping in the landfill.

In a comparable study held in the Kingdom of Saudi Arabia (KSA) by the study of Sadiq and Kaneesamkandi [23], biogas yield of an average value of 450 m^3/ton organic waste was approved based on experimental based literature. For this reason, the approximate biogas yield from organic waste generated in the KSA found to be 3,420.50 million m^3/y from which 1 ton OW can generate about 398 kWh of energy. However, the Official Information Portal on Anaerobic Digestion in the UK outlined that digesting 1 ton of food waste can generate about 300 kWh of energy, considering the electricity cost by Electricity and Water Authority (EWA) in Bahrain which is 0.02 USD/kWh. Since the KSA is a Gulf country and shares many similarities with Bahrain in terms of lifestyle, culture, etc., the value considered to estimate the electricity generated from the biogas yield is 398 kWh/ton biodegradable waste and therefore, was used as a reference in this study. Table 4, outlines the benefit from electricity sales in USD. The baseline case is considering 10% discount rate, which represents the current status. Sensitivity analysis was conducted to assess the feasibility at two different scenarios: Discount rate at 5% and 20% as shown in Tables 7 and 8, respectively.

Table 1
Waste categories by weight in ton in the last 2 y in Bahrain, which are dumped into Askar Landfill

Waste category	2018	2019	Average
Dead animals	8,031	11,971	10,001
Building waste	831,609	322,472	577,041
Commercial waste	347,827	333,093	340,460
Construction waste for recycling		355,690	355,690
Domestic waste	563,915	566,125	565,020
Garden waste	124,324	126,107	125,216
Industrial waste	81,577	81,175	81,376
Buhair Area waste	509,449		509,449
Total	2,466,733	1,796,633 Avg. total:	2,131,683

Table 3
Total Bahrain's biodegradable waste composition in ton/y

Description	Ton/y
Total domestic biodegradable waste (food, papers, green)	221,942
Total garden waste	125,216
Dead animals	10,001
Total commercial biodegradable waste	136,184
Total industrial biodegradable waste	21,158
Total WWTP sludge	20,750
Total biodegradable waste in Bahrain	535,251

Table 2
Total biodegradable waste under each category in Bahrain

Biodegradable waste in Bahrain ton/y	Commercial	Industrial	Domestic, garden and dead animals	Sludge from WWTP	Total
Total waste	340,460	81,376	567,542	20,750	1,010,128
Total biodegradable waste	136,184	21,158	357,159	20,750	535,251
Percentage of biodegradable waste from total waste	40	26	63	100	53

Table 4
Biogas yield and electricity sales estimation for Bahrain

Total BDW	Biogas m^3/ton	Total biogas yield (m^3)	kWh/ton	Total energy output (kWh)	Total energy output (GWh)	Electricity cost (USD)	Annual revenue (USD)
535,251	450	240,862,950.00	398.5	213,297,523.50	213.30	0.02	4,265,950

5. Results and discussion

From Table 4, it is obvious that the AD Plant is expected to generate 213.3 GWh/y, with annual revenues of USD 4,265,950 from electricity sales. Furthermore, according to the MWMUP, the cost of dumping of 1 ton of waste in the landfill is USD 16, so there will be a saving by discontinuing the total biodegradable waste dumping. In addition, from the literature, it was found that each ton of organic waste produces 0.2 ton of fertilizer. Cost estimates of an anaerobic digestion plant in developing countries were mentioned by the study of Cioabla et al. [9] who showed that the capital cost of AD is 18$/ton in average. While he stated that the O&M cost is 14.5$/ton. Accordingly, the total capital cost and the total O&M cost were calculated based on these prices for an AD of 536,000 ton/y capacity for Bahrain. Table 5 presents the cost-benefit analysis of an AD plant for the Kingdom of Bahrain assuming that the capital cost is a fixed cost which is paid during the first year of the project, whereas the operation and maintenance cost (O&M cost) represents the cash out flow, which is the annual cost considered in calculating the net profit. The benefit is expressed as sales revenues from the digestate that can then be used as fertilizer to enhance the soil in agriculture. Since the net profit number is positive and is high, it can be inferred that the AD project itself is primarily considered to be a viable solution to manage the biodegradable waste in the Kingdom of Bahrain, after calculating the Net Present Value (NPV) that must also be positive. The NPV is the difference between the present value of cash inflows and the present value of cash outflows. NPV is used in capital budgeting to analyse the profitability of an investment or project. It measures the excess or shortfall of cash flows, in present value terms, once financing charges are met [24]. In addition, the internal rate of return (IRR) is defined as the interest rate at which the net present value of costs (negative cash flows) equals the net present value of the benefits (positive cash flows). An investment is considered acceptable if its IRR is greater than an established minimum acceptable rate of return or cost of capital [24]. Furthermore, the payback period (PBP) indicates the amount of time it takes for a capital budgeting project to recover its initial cost. In capital budgeting, payback period denotes the period of time required for the return on an investment to "repay" the sum of the original investment. To calculate it, the payback period equals Investment required divided by Net annual cash inflow [24]. Considering the discount rate of 10%, the net present value (NPV), the internal rate of return (IRR) and the payback period (PBP) were calculated in this study for the AD plant project based on the CBA as shown in Table 6. The cash flow of the baseline case suggests that the AD is a viable project, since the NPV is positive and worth around USD 33.5 M, with an internal rate of return (IRR) that reached 59%, and a payback period of 1.7 y, which indicated the viability of the project.

By applying a sensitivity analysis, considering discount rate 5% and 20%, the project remains feasible and viable. The NPV is USD 49.3M when the discount rate is 5%, while it is USD16.9M considering the discount rate 5%.

Table 5
Cost-benefit analysis of AD plant for the Kingdom of Bahrain

Description	USD
Capital cost/ton	18
O&M cost/ton	14.4
Total capital cost	9,634,518
Total O&M cost	7,707,614
Benefits/y	
Electricity	4,265,950
Fertiliser	642,301
Direct saving by discontinuing waste dumping	8,473,705
Total benefit/y	13,381,957
Net profit	5,674,342

Table 6
Cash flow with NPV, IRR and PBP of the AD plant project for Bahrain (Baseline case: discount rate 10%)

Period	Cash flow
0	(9,634,518)
1	5,674,342
2	5,674,342
3	5,674,342
4	5,674,342
5	5,674,342
6	5,674,342
7	5,674,342
8	5,674,342
9	5,674,342
10	5,674,342
11	5,674,342
12	5,674,342
13	5,674,342
14	5,674,342
15	5,674,342
Discount rate	10%
NPV	33,524,979
IRR	59%
PBP	1.7

In the other hand, if the project was achieved under the discount rate 10%, with continuing the dumping with no saving earned from it accordingly, the project will not be feasible nor viable, at all discount rates (5%, 10% and 20%), as shown in Tables 7–11, thus discontinuoing dumping and earn the savings is a condition to guarantee ensure the project feasibility and viability for Bahrain.

5.1. Environmental benefit

According to Mutz [25] and Lee et al. [26], the conversion of organic waste to biogas is associated with a number of environmental benefits. Biogas from organic waste reduces the emission of greenhouse gases into the atmosphere [25] resulting from organic waste dumping [26]. Each tonne of organic waste dumped in the landfill releases about 1 ton of carbon dioxide equivalents (CO_2-e) in the form of methane [27]. Consequently, dumping of 535,251 ton/y of biodegradable waste in the landfill results in 21,410 ton CH_4/y (1 ton biodegradable waste results in 0.04 ton CH_4), which is equivalent to 535,251 ton CO_2-e/y. Therefore, the AD project contribute to GHG emission reduction since the landfill methane has a global warming potential of approximately 25 times higher than that of CO_2 [25]

6. Conclusion

Accordingly, the cost-benefit analysis in this study gives an economic evidence to recommend AD to the decision makers as a feasible option to manage the biodegradable waste in the Kingdom of Bahrain, which can then be embedded into the national legal and policy frameworks. AD is receiving increasing attention as a possible option of energy recovery from waste in the urban context. However, the operation of biogas plants from heterogeneous MSW

Table 7
Sensitivity analysis: cash flow with NPV, IRR and PBP of the AD plant project (discount rate 5%)

Period	Cash flow
0	(9,634,518)
1	5,674,342
2	5,674,342
3	5,674,342
4	5,674,342
5	5,674,342
6	5,674,342
7	5,674,342
8	5,674,342
9	5,674,342
10	5,674,342
11	5,674,342
12	5,674,342
13	5,674,342
14	5,674,342
15	5,674,342
Discount rate	5%
NPV	49,263,212
IRR	59%
PBP	1.7

Table 8
Sensitivity analysis: cash flow with NPV, IRR and PBP of the AD plant project (discount rate 20%)

Period	Cash flow
0	(9,634,518)
1	5,674,342
2	5,674,342
3	5,674,342
4	5,674,342
5	5,674,342
6	5,674,342
7	5,674,342
8	5,674,342
9	5,674,342
10	5,674,342
11	5,674,342
12	5,674,342
13	5,674,342
14	5,674,342
15	5,674,342
Discount rate	20%
NPV	16,895,713
IRR	59%
PBP	1.7

Table 9
Sensitivity analysis: cash flow with NPV, IRR and PBP of the AD plant project when continuing dumping (discount rate 10%)

Period	Cash flow
0	(9,634,518)
1	(2,799,362)
2	(2,799,362)
3	(2,799,362)
4	(2,799,362)
5	(2,799,362)
6	(2,799,362)
7	(2,799,362)
8	(2,799,362)
9	(2,799,362)
10	(2,799,362)
11	(2,799,362)
12	(2,799,362)
13	(2,799,362)
14	(2,799,362)
15	(2,799,362)
Discount rate	10%
NPV	–30,926,688

Table 10
Sensitivity analysis: cash flow with NPV, IRR and PBP of the AD plant project when continuing dumping (discount rate 5%)

Period	Cash flow
0	(9,634,518)
1	(2,799,362)
2	(2,799,362)
3	(2,799,362)
4	(2,799,362)
5	(2,799,362)
6	(2,799,362)
7	(2,799,362)
8	(2,799,362)
9	(2,799,362)
10	(2,799,362)
11	(2,799,362)
12	(2,799,362)
13	(2,799,362)
14	(2,799,362)
15	(2,799,362)
Discount rate	5%
NPV	–38,690,938

Table 11
Sensitivity analysis: cash flow with NPV, IRR and PBP of the AD plant project when continuing dumping (discount rate 20%)

Period	Cash flow
0	(9,634,518)
1	(2,799,362)
2	(2,799,362)
3	(2,799,362)
4	(2,799,362)
5	(2,799,362)
6	(2,799,362)
7	(2,799,362)
8	(2,799,362)
9	(2,799,362)
10	(2,799,362)
11	(2,799,362)
12	(2,799,362)
13	(2,799,362)
14	(2,799,362)
15	(2,799,362)
Discount rate	20%
NPV	–22,722,858

poses a major challenge in terms of operational, safety and financial requirements. As a consequence, there are very few successful examples of biogas from biodegradable waste and sewage sludge in developing countries, due to the absence of segregation at source and mixed waste [7].

This study has concluded that the establishment of an AD plant in Bahrain for the treatment of biodegradable waste going to the landfill annually, is expected to generate 213.3 GWh/y, with annual revenues of USD 4,265,950 from electricity sales. The second source of revenues from this project is expected from the sales of the fertilizer produces as another end product with the biofuel, with a sales revenues of USD 642,301 considering that each ton of organic waste produced 0.2 ton of digestate, so this project is expected to produce 107,050 ton of digestate to be used as a fertilizer, with the international sale price of USD 6/ton. The direct saving earned by discontinuing biodegradable waste dumping of 535,251 ton/y in the landfill, is about USD8.47 M which will be saved annually and increase the viability of the project.

The cash flows suggests that the AD is a viable and feasible project with a condition of discontinuing waste dumping and earning the savings. The NPV is positive and worth around USD 33.5 M, with an internal rate of return (IRR) that reached 59%, and a payback period of 1.7 y, which indicates the viability of the project, considering the discount rate 10%. While it reaches USD49.3 M when the discount rate is 5%, while it becomes USD16.9 M considering the discount rate 5%.

In the other hand, if the project was achieved under the discount rate 10%, with continuing the dumping with no saving earned from it accordingly, the project will not be feasible nor viable, at all discount rates (5%, 10% and 20%).

Moreover, 535,251 ton/y of CO_2-e can be reduced by discontinuing biodegradable waste dumping into the landfill after implementing the AD plant project, assuming the existing biodegradable generation rate in the Kingdom of Bahrain.

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