Chapter

A Comparative Study of MSW to Emery in Oman

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Abstract

The adverse impact of the energy production from fossil fuels is now well recognized globally; therefore, the move toward renewable and sustainable energy has become an integral part to achieve the United Nations Sustainable Development Goals (SDGs). This chapter presents a comparative study considering a waste-to-energy plant to produce electricity in Oman. A research strategy that includes both qualitative and quantitate research methods were adopted to evaluate the MSW generation and emissions, electricity consumption and emissions, public participation in waste segregation, and to estimate the reduction in emission by considering a 5000 tons/day waste-to-energy plant in Oman. The results show that the current emission from fossil fuels to meet the electricity requirement of 70,633.37 Million kWh/year is 161.781 Million tonnes (CO_2/year). Similarly, the emissions from MSW which currently stood at 2.159 million tons/year are 3,424,247 tons CO_2/year. A 5000 ton per day waste-to-energy plant will not only produce 29.30 million kWh daily but will also enable an annual reduction of 24,527 million kg CO_2. Such an initiative will help Oman to improve its sustainability performance in energy, climate change, waste reduction, and economic growth and will pave the road to achieve the relevant SDGs by 2030.

Keywords: energy, sustainability, waste management and disposal

1. Introduction

Energy is an integral part of today's modern life, but the way most the energy is produced around the world creates several environmental and sustainability issues. Environmental sustainability is the core issue that needs to be addressed for development to focus on human well-being and yet stay within the limitations of the planet's capacity. Environmentally sound waste management is one of the key elements for sustainable development. The idea of sustainability developed in the early 1980s as reported in the International Geosphere-Biosphere Program can be defined as "meeting fundamental human needs while preserving the earth natural environment" [1]. Since the earth's population is increasing, it is putting pressure on the earth's resources. According to the World Economic Forum, it is estimated that food production will need to double by 2050 to feed 10 billion people on the earth [2]. Today, sustainability has three essential pillars, including environmental protection, social development, and economic growth; sustainable development can be been defined as a development that meets the needs of the present without compromising the ability of future generations to meet their own needs [3]. The need for sustainable development is truly recognized by all countries, and thus in 2015, the United Nations (UN) was able to introduce 17 Sustainable Development Goals (SDGs) to be achieved by 2030 [4]. The UN under Goal 12 (Responsible Consumption and Production) of its SDGs aims to substantially reduce waste generation through prevention, reduction, recycling, and reuse. Data from 214 cities or municipalities in 103 countries show that about three quarters of MSW generated is collected (**Figure 1**). In sub-Saharan Africa, less than half of all MSW generated is collected, with adverse effects on the health of residents. Moreover, even when waste is collected, it is often not treated and disposed of in a sustainable and environmentally sound manner. Managing such wastes continues to be a major challenge facing urban areas in several regions. Appropriate waste management is important for conserving local and global environments. Improvement of waste management in developing countries is directly related to preventing environmental pollution and expanding public health services. Appropriate waste management contributes to reducing not only the emission of water/atmospheric pollutants and odors but also the emission of greenhouse gases. In this regard, some studies reported that Green House Gases (GHG) emissions from the waste sector contribute to 3–4% of total global GHG emissions [7]. The rapidly increasing amount of municipal waste in cities around the globe is connected with economic development, as an increase in the city population creates many major challenges associated with economic development [8].

Gulf Cooperation Council (GCC) member countries (Saudi Arabia, Oman, United Arab Emirates, Kuwait, and Qatar) are considered as major consumers of the natural resources, which results in a huge amount of emissions [9, 10]. Similarly, the annual solid waste generation in the GCC region has exceeded 150 million tons. GCC countries feature among the world's top 10 per capita waste generators (**Figure 2**). Similarly, the annual solid waste generation in the GCC region has exceeded 150 million tons. Comparatively, this is lower than the waste generated in the UK, as GCC has a lower population (≈54 million) than the UK (66 million); however, at the same time; the UK recycles more than 45% of its waste [12]. The recycling of waste in the GCC is almost zero. Lack of legal and institutional frameworks has been a major stumbling block in the progress of the waste management sector [11]. The per capita production of municipal waste in top GCC cities, such as Riyadh, Doha, Abu Dhabi, and Dubai, is more than 1.5 kg per day which is among the highest worldwide [13]. Some recent studies which considered situations of waste in the whole gulf region indicate that the recycling sector is underdeveloped and hardly 10–15% of the waste is recycled [14]. This chapter considers the MSW in Oman to produce electricity. Currently, the MSW

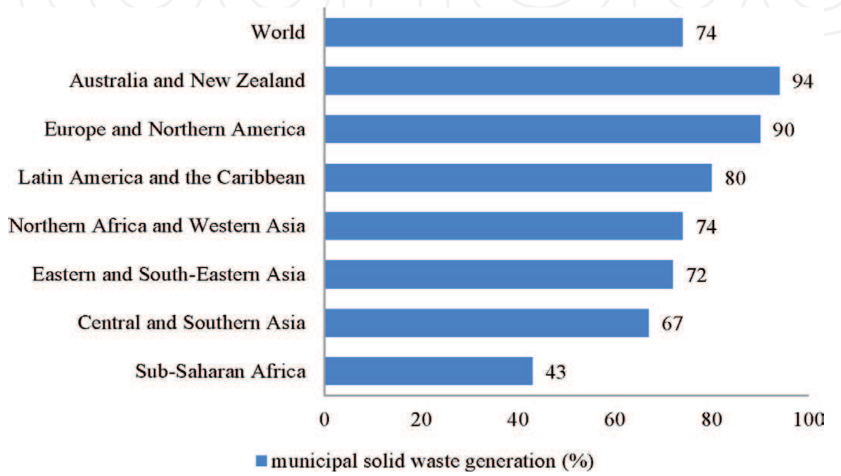

Figure 1.
Proportion of the municipal solid waste generated that is collected, 2001–2015 (data from 214 cities/municipalities in 103 countries) [5, 6].

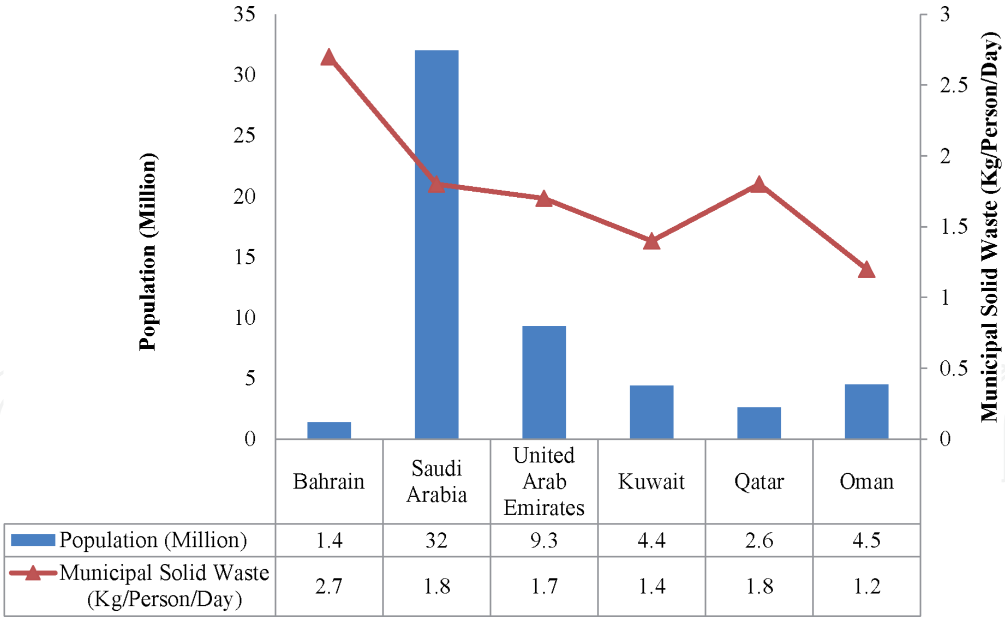

Figure 2.
GCC population versus municipal waste generation [6, 11].

in Oman is deposited in more than 300 landfills/dumpsites managed by municipalities. Overall, most of the solid waste is sent to authorized and unauthorized dumpsites for disposal, which is creating environmental and health issues. There are several dumpsites which are located in the midst of residential areas or close to catchment areas of private and public drinking water bodies. Similarly, these landfill stations occupied a large area of land which can be utilized for some other purposes. For instance, as per the Ministry of Housing regulations, each Omani is eligible to get a plot of 500 sqm for the house after reaching a certain age [15]. Of course, this is a non-sustainable approach, but this is the current policy of the government, and thus the reduction in landfills will help Oman to fulfill such commitment in a more appropriate manner. Similarly, a survey conducted by the Be'ah, a company established under the Royal Decree 46/2009, shows that solid waste in Oman is characterized by a very high percentage of recyclables, primarily paper and cardboard (15%), plastics (20.9%), metals (1.8%), and glass (4%) [16]. Some of the newspaper reports show that currently 100% of the MSW in Oman goes to landfills [17].

To reduce GHG emissions from MSW and to reduce the burden of landfills on the earth, proper disposal and recycling of MSW are important. One of the modern methods that are recently adopted by many countries is to use MSW in a plant to produce energy. This type of plant is commonly known as waste-to-energy plants. The aim of this research is therefore to explore the opportunities to use MSW for electricity production in Oman. Such opportunities, however, cannot be understood well without knowing the composition of the MSW, public participation, and cooperation in activities related to recycling. This research, therefore, incorporates both quantitative and qualitative approaches, commonly known as mixed method, were adopted to accomplish the aims and objectives set for the research. The next section provides a literature review, covering Oman energy situation, electricity consumption, and the types of waste-to-energy plants.

2. Literature review

Although energy has become an integral requirement of today's modern life and it is considered as a fundamental element for social and economic growth, however, the United Nations report indicated that 13% of the earth's populations still have no access to modern electricity. Similarly, more than 3 billion people are still using wood, coal, charcoal, or animal waste for cooking their food and heating purposes. Energy is considered as the dominant contributor to climate change, which is estimated to be around 60% of total global greenhouse gas emissions. Similarly, it is estimated that in 2012, the indoor air pollution from using combustible fuels for household energy caused 4.3 million deaths around the world [18]. Overall, most of the current energy production is based on conventional resources such as oil, gas, and coal which, on the one hand, are non-sustainable but also, on the other hand, these resources produce greenhouse gases. These gases are considered a threat to the earth due to its contribution to global warming and climate change. The main gas which highly contributes to global warming and climate change is CO_2. The emission of the CO_2 to the earth's atmosphere has been significantly increased since 1950 which has reached a level of 400 parts per million (ppm). The CO_2 emission during the past 800,000 years until 1950 was below the level of 300 ppm [19].

Majority of the greenhouse gases are regarded as manmade gases in which the major role has been played by the recent industrialization. Although, the issue of global warming and climate change is well regarded as a threat to human life on the earth and there have been several efforts to control the emissions which cause global warming and climate change, the data from different sources reflect that these emissions are still increasing. For instance, the global CO_2 emission from fossil fuels in 2010 was 33.1 gigatons which have increased to 37.1 gigatons in 2018, representing a total increase of 12.08%. This emission quite alarming and if not tackled properly, and if it is increased at the same level, it would reach 41.58 gigatons by 2028 [20].

Goal 7 of the UN SDGs is "Affordable and Sustainable Energy" under which the member countries agreed to ensure access to affordable, reliable, sustainable, and modern energy. This goal is further supported by five global targets as mentioned below:

Target 1: By 2030, ensure universal access to affordable, reliable, and modern energy services.

Target 2: By 2030, increase substantially the share of renewable energy in the global energy mix.

Target 3: By 2030, double the global rate of improvement in energy efficiency.

Target 4: By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency, and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology.

Target 5: By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular, least developed countries, Small Island, developing States, and land-locked developing countries, in accordance with their respective programs of support.

To effectively understand the energy requirement of GCC countries, the electricity consumption and CO_2 emission in these countries are considered in the first instance. As the gulf region is rich in oil and gas reserves, therefore this region is considered as the main producer and supplier of the energy. The oil and gas revenue constitutes a major portion of the gross domestic product (GDP) in most of the GCC countries and remained support for the government and industrial sectors [21]. At the same time, the region is also a main consumer of energy as compared with other countries around the world. Similarly, due to the high rate of electricity consumption in these countries, the CO_2 emission is also high as presented in **Figure 3**. High electricity consumption and CO_2 emission could be justified due to the climatic condition of the region where the temperature in summer reaches 50°C as reported by Umar and Egbu [24], however, such

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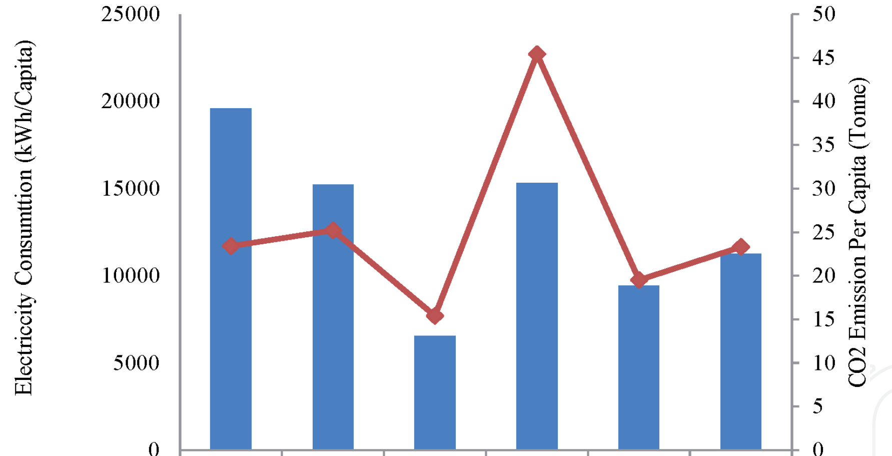

	Bahrain	Kuwait	Oman	Qatar	Saudi Arabia	United Arab Emirates
Electriccity Consumttion (kWh/Capita)	19592.232	15213.42	6553.52	15309.429	9444.216	11263.532
CO2 Emission Per Capita (Tonne)	23.4	25.2	15.4	45.4	19.5	23.3

Figure 3.
Electricity consumption and CO_2 emission per capita in GCC countries [22, 23].

consumption and emissions are more than the double when compared with other countries. For instance, the average electricity consumption in GCC countries [=12,896.058 kilowatt-hours (kWh)] as of 2014, is more than three times greater than the electricity consumption in China (=3927 kWh) [22]. Similarly, the GCC electricity consumption per capita is more than double the consumption in the United Kingdom (=5130 kWh). It is very difficult to justify so high consumption of electricity in the GCC region based on the argument that it has a hot climatic condition. if this argument is considered to be true, then a high consumption is to be expected from the United Kingdom as well, as it has a cold climatic condition, however, the consumption in the united kingdom is far low than the average consumption of the GCC. Similarly, the average CO_2 emission is GCC countries (=25.36 tons) is more than three times greater than the CO_2 emission per capita in China (=7.5 tons) and almost four times greater than the CO_2 emission per capita in the United Kingdom (=6.5 tons) [23]. The main reason for this high CO_2 emission in GCC countries is that most of the electricity in these countries is produced by oil and gas. For instance, in Saudi Arabia, a total of 330.5 billion kWh of electricity was generated in 2016. 40.30% of this electricity was produced from oil, 59.6% was produced by gas, and only 1% was produced from renewable resources [25]. Similarly, according to the British Petroleum report, 68% of the electricity in Oman is produced by gas while the remaining 32% is produced by oil. Overall, the share of GCC countries in the renewable section is almost negligible. At the same, in other parts of the world, research is in progress to explore how to meet the full energy requirement of cities through renewable sources [26, 27]. Thus, it is obviously clear that a huge emission could be expected from these countries when all of its energy requirements will be met from fossil fuels.

Different estimates show that 0.0016 barrels of oil is required to produce 1 kWh of electricity and one barrel of oil produces 0.43 tons of CO_2 [28, 29]. To clarify the situation more effectively, the total electricity consumption per capita in the GCC region is 77376.349 kWh and the total CO_2 emission in this region is 152.2 ton (=152,200 kg). In other words, the CO_2 production per capita per kWh in the GCC region stands at 1.97 kg (1.97 kg/kWh). This further reveals that the CO_2 production for China (=1.90 kg/kWh) and United Kingdom (1.26 kg/kWh) is lower than the GCC region. As shown in **Figure 4**, the high consumption of natural resources has derailed the progress of both the relevant goals of UN SDGs, Goal 12 (Responsible Consumption and Production) and Goal 13 (Climate Action). On the other hand, Denmark which is ranked first in terms of progress toward UN SDGs has achieved a score of 90.20 (out of 100) in Goal 13 [30].

The move of the GCC region toward renewable energy may change these figures and could enable the region to reduce its emission per kWh. Oman has particularly low oil and gas reserves, therefore, it is important for the country to take advantages from other resources that are available and can be used for electricity production so that that the pressure on its oil and gas reserves can be reduced and as such can stay for long [31]. Despite the fact that Oman has comparatively low oil and gas reserves, its progress toward renewable recourses is low [32]. Similarly, both the Omani visions 2020 and 2040 stress to reduce the dependency on the oil and gas revenue and on the action plan mentions that improve MSW collection service. These visions also emphasize that improved MSW collection and disposal system are mandatory to reduce the impact on the natural environment [33, 34].

One of the resources that have been used by many countries to produce electricity is waste. For instance, Japan is using 72% of its waste to produce energy, while the United States is using approximately 13% of the waste for the same purpose. The top leading countries around the world which are using waste for energy production along with the percentage of the waste they are using for such purpose as shown in **Figure 5**. There is an opportunity for Oman to take advantage of the waste-to-energy technique and produce a share of its energy requirement from the MSW as other countries are doing. This will not only help to reduce the burden of the Oman oil and gas reserves but will also help to minimize MSW impact on the natural environment.

There are three types of combustion technologies that can be used to produce energy from MSW [36]. The mass-burn facilities are the most common type of waste-to-energy plants installed in the United States [37]. In some types of plants, it is necessary to segregate the MSW before it is moved to the combustion chamber while in other it is not necessary. The segregation of waste before entering the burn unit allows extracting the recyclable materials from the waste [38]. In most cases, the mass-burn facilities are made to burn the waste in one burning chamber allowing excess air. In the combustion process, excess air must be allowed to promote turbulence and mixing so that air can reach all waste. This process is important due to the inconsistent composition of MSW. In a common mass-burn plant, the MSW is

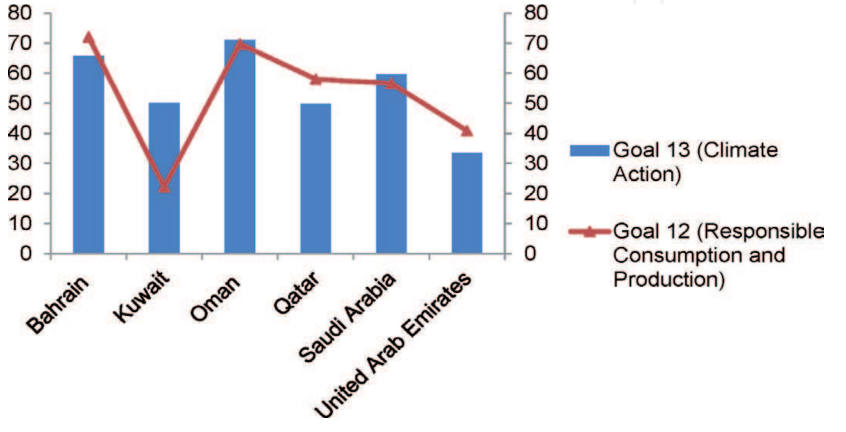

Figure 4.
Goals 12 and 13 score of different GCC countries.

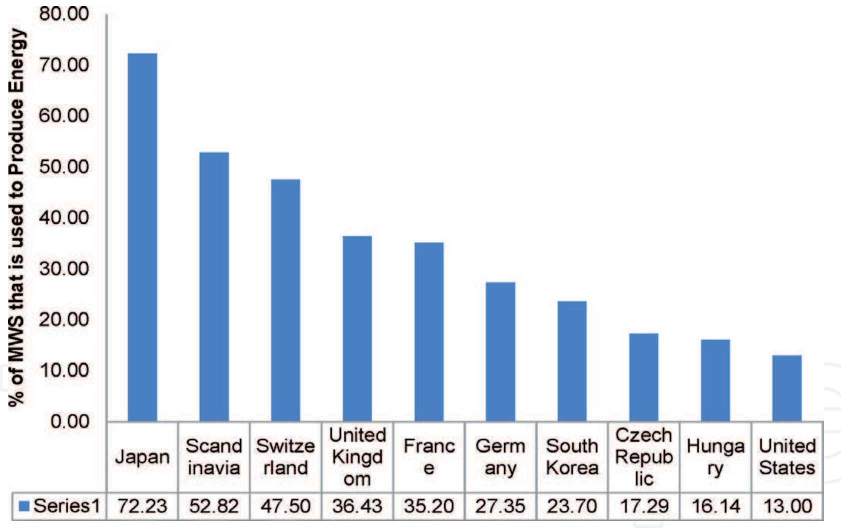

Figure 5.
Percentage of waste that is used for energy production in different countries [35].

burned in a sloping and moving grate. The vibration allows the blending of MSW and helps it to mix with air. Similarly, the modular systems are made to combust the unprocessed and mixed waste. Such plants are quite smaller when compared with the mass-burn unit and therefore can be moved from one site to another site easily [39]. The third type of waste-to-energy plants are known as "Refuse Derived Fuel Systems." Such plants apply mechanical systems to segregate the MSW and allow only combustible materials and mixtures to be used in the furnace or in a conventional boiler system [40, 41].

The research methodology used in this research is explained in the next section.

3. Research approach

Both the qualitative and quantitative research strategies were employed to obtain the aims and objectives set for this research. Since the quantity and the composition of the MSW are important to know energy content and emissions, therefore, the samples of MSW were collected from different households. To know the composition of the MSW in Oman, a total of 238 samples collected from 25 residential houses (175 samples), four restaurants (28 samples), three shopping markets (21 samples), and two hotels (14 samples) as shown in **Table 1**. The houses were selected in a way so that the reliability could be achieved. Thus, the houses with the family members of 2, 3, 4, 5, and 6 were considered for data collection. Samples of waste were collected from each house on a 24-hour basis. The same approach was adopted to collect the samples from restaurants (four numbers), shopping markets (three numbers), and hotels (two numbers). The samples were collected on each day of the week. The samples were deposed in the municipality collection point after recording the required data. Every morning the samples were collected, segregated, and measured. The data collection was completed in 2 months, from June 27, 2019 to August 26, 2019. The segregation method adopted was according to the criteria followed in the 3R projects implemented by Japan International Cooperation Agency (JICA) in Hanoi [42–44].

Additionally, the residents' willingness and participation in recycling activities were captured through an interview conducted at the time of sample collection. A total of 34 interviews, 25 from residential houses, four from restaurants, three from shopping markets, and two from hotels were conducted. The sample used to know

Type of entity	Number of samples per day (24 hours)	Number of days samples were collected	Number of entitles used for sample collection/interview	Total samples
Residential houses	1	7	25 (one sample from each houses with family members of 2, 3, 4, 5, and 6)	175
Restaurants	1	7	4	28
Shopping markets	1	7	3	21
Hotels	1	7	2	14
Total:			34	238

Table 1.
MSW samples collection approach.

the residents' willingness and participation was considered appropriate as there is evidence in the existing literature that similar studies were conducted with much smaller samples. For instance, Mason [45], in his research entitled "Sample Size and Saturation in Ph.D. Studies Using Qualitative Interviews," reported the result of 560 studies and noted that the most common size of the sample in these studies was 20. Similarly, Umar [46], while developing an integrated approach to promote sustainability in university campuses, used a sample of 20 respondents. Although the questionnaire used for this purpose was prepared in English, due to the diversity of the respondents, the interview process was deemed fit to the respondents. Overall, 45% of the residents in Oman are expatriates and the majority of them belong to some Asian countries [47]. The participants in the data collection were therefore interviewed in the local language so that there could be no communication barriers.

The environmental performance of the current approach of MSW management was measured through the emissions produced by landfills. The Intergovernmental Panel on Climate Change (IPCC) 2006 model is used to calculate GHG emissions from landfills [48]. IPCC model is an international model used by The United Nations Framework Convention on Climate Change (UNFCCC) member countries to report the national GHG inventory. Eq. (1) is used to calculate the CH_4 emission from landfills. Similarly, for the environmental performance of waste-to-energy approach, different parameters such as emissions per tons, reduction in landfills, and energy production and social indicators such as employment were considered. For instance, Eq. (2) was used to determine the emissions from crude oil when used in electricity production. In the comparison of emissions from both scenarios, landfilling and waste-to-energy approach, the emissions produced from the transportation of waste were ignored. Such emissions include the GHG emission from the transportation of waste from the collection point to the recycling facility for which trucks are commonly used [49].

$$CH_4 = \left[\left(MSW_{(Land\ Fill)} \times MCF \times DOC \times DOC_f \times F \times (16/12) - R\right) \times (1 - OX)\right] \quad (1)$$

where CH_4 = methane emission in Gg/year (1 Gg = 10^9 g; 1 Gg = 1000 ton), $MSW_{(Land\ Fill)}$ = total amount of MSW in the landfill in wet weight basis (Gg/year), MCF = CH_4 correction factor—value used in the calculation = 0.6, DOC = the fraction of degradable organic carbon in MSW (Gg C/Gg MSW)—value used in the calculation = 0.2455, DOC_f = the fraction of DOC that can decompose (fraction)—value used in the calculation = 0.77, F = the fraction of CH_4 in generated landfill gas—value used in the calculation = 0.5, R = the recovered CH4 (Gg/year), 16/12 is the molecular weight ratio CH_4/C—value used in the calculation = 0, and OX = the oxidation factor—value used in the calculation = 0.

$$E = A\,x\,B\,x\,C\,x\,D \tag{2}$$

where E = CO_2 emission per barrel (tons), A = the average heat content of the crude oil (=5.80 mmbtu per barrel; mmbtu = one million British Thermal Units), B = the average carbon coefficient of crude oil (=20.31 kg carbon per mmbtu), C = the fraction oxidized (=100% [48]), and D = the ratio of the molecular weight of carbon dioxide to the carbon (=44 kg CO_2/12 kg C) [9, 50].

Similarly, the electricity content and emissions from the MSW was established considering the existing literature. Different keywords such as "electricity content in MSW," "energy production from MSW," "waste-to-energy plant," and "emissions from energy to waste" were used in the main search engines. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were adhered to during the review process [51]. Different results associated with the electricity content and emissions from waste-to-energy plants were obtained from the systematic review. For instance, in the United States, there are 68 waste-to-energy power plants that produce about 14 billion kilowatt-hours (kWh) of electricity using 26.76 tons of combustible MSW [52]. In other words, the energy or electricity content per tons of MSW in the United States is approximately 586 kWh. The waste-to-energy plant installed in Qatar which has a capacity of 2300 tons per day produces 50 Mega Volt Amp (MVA) which is equal to 40,000 kWh per day [53]. Similarly, the statistics issued by Waste Management World indicates that electricity production from MSW can be up to 875 kWh per ton of MSW processed in a waste-to-energy plant [54]. The calculation presented in this chapter, however, considers a value of 586 kWh per MSW used in a waste-to-energy plant, keeping in mind that this value is from the United States which uses the same types of waste to plant as proposed in this research.

The total waste which is burned for energy recovery in the United States currently stood at 12.70% of the total waste. Apart from producing energy, the burning of waste can reduce the volume of waste by 90%. Similarly, a recent waste-to-energy plant constructed in Ethiopia uses the same approach of burning waste to produce electricity. The collected waste is kept for 5 days to allow the moisture to seep out and then burning the waste at 1000°C to turn it to heat energy to run the steam turbine [55]. The latest and modern waste-to-energy plant can reduce the emissions (CO_2) ranging from 100 to 350 kg CO_2 equivalent per ton of the MSW used [56]. An average emission reduction value of 225 kg CO_2 equivalent to per ton of MSW can be used to measure such reduction in emission; however, the Environmental Protection Agency (EPA) of the United States reveals that the burning of 1 ton MSW in a waste-to-energy plant results in 1 ton of less CO_2 when compared to the common practice of landfilling [57]. The potential reduction in emissions between landfilling and waste-to-energy plants investigated by Wang et al. [58] in China noted that such reduction can be more than 1000 kg per ton. Similarly, the study conducted by Obermoser et al. [59] to establish a reliable CO_2 value from waste-to-energy plant noted that CO_2 emission can be in the range of 30–67 kg CO_2 per Giga Joule which can be translated into 0.175 kg CO_2 per kWh.

The next section describes the results and analysis made from the data collected in Section 3.

4. Results and analysis

Considering the different aspects of the results and analysis, this section is divided into different subsections. The first subsection describes the results and analysis of the MSW composition and the public participation in the MSW segregation.

4.1 MSW composition and public willingness

As noted in Section 3, a total of 175 samples were collected from the residential houses. These samples were used to determine the MSW generation per capita. The results show that the mean weight of the MSW samples was 1.3 ± 0.28 kg/per capita. Currently, as of May 2020, the total Oman population stands at 4,613,726, which can be translated into a total of 5998 tons MSW generation per day in Oman [60]. Similarly, the whole samples collected from the residential houses, restaurants, shopping markets, and hotels were used to determine the MSW composition in Oman. This composition is reported in **Figure 6**. Overall, the composition of the MSW represents a good percentage of waste that can be combustible and suitable to be used in a waste-to-energy plant to produce electricity.

During the MSW sample collection process, the inhabitants were asked about their cooperation and participation in the waste segregation activities. The willingness of the residents was considered important as this may be helpful to transfer only the MSW that is suitable to be used in the waste-to-energy plant. In other words, when the residents will segregate the waste at their own, the process at the waste-to-energy plant will become more straightforward as it will receive only the waste which could be used in the plant. A total of 34, consisting of 67.64% male and 32.35% female face-to-face interviews were conducted during this stage. All the participants appraised the idea of using MSW for electricity generation. A large number of the interviewees (70.58%) agreed that they are willing to participate in the segregation of the MSW at their doorsteps. The remaining participants did not answer as no but they were somehow not sure how they can do such segregation.

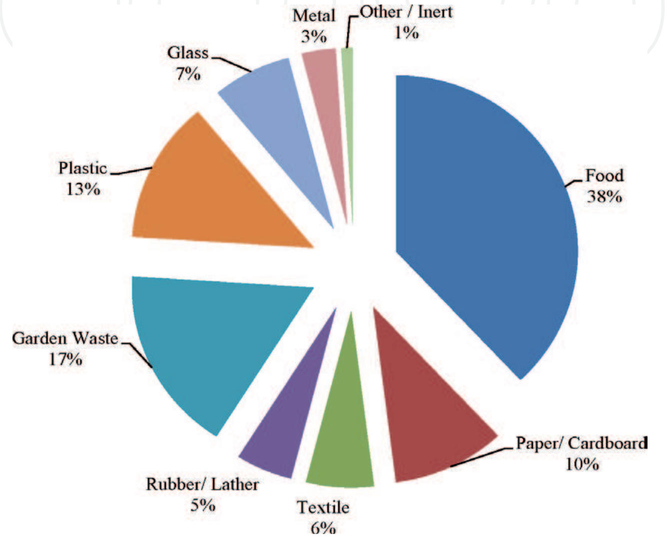

Figure 6.
Composition of MSW in Oman.

Overall, the majority of the respondents (79.94%) noted that they required some sort of training and tools to do such tasks in their homes.

The next section outlines the emission from MSW considering the landfilling scenario.

4.2 Emissions from MSW

To calculate the emissions from MSW using Eq. (1), DOC for different waste materials was obtained from the IPCC and the Atmospheric Brown Clouds Emission Inventory Manual (ABC EIM). Based on these two documents, the DOC paper = 0.25, DOC food = 0.4, DOC textile = 0.25, and the DOC rubber = 0.39 were considered. The average DOC value was calculated based on the above values and waste fraction as shown in **Figure 6**. The final DOC value used in the calculation, therefore, stands at 0.2455. The total MSW waste considered in this calculation was equal to 2,159,219 tons per year or 2159 Gg per year. This MSW produces a total of 163,060 Gg/year CH_4 which is equal to 3,424,247 tons/year CO_2 equivalent. This can be translated into the emissions produced 1 ton, which can be equal to 1.58 ton per year CO_2 equivalent per ton of MSW.

The next section describes the electricity consumption, production, and emissions produced by such consumption and production.

4.3 Electricity production and emissions

In terms of electricity production, Oman is using both oil and gas to meet its electricity requirement. As noted in **Figure 3**, the current consumption of electricity per capita in Oman is 15,309.4 kWh per year that can be translated into total energy consumption by multiplying this figure with the total population of Oman (15,309.4 × 4,613,726), which gives a total consumption of 70,633.37 million kWh per year. To calculate the emissions from electricity production through oil and gas, 70% of the electricity production is considered to be from oil, and 30% is considered to be from natural gas. These percentages were taken from the study conducted by the Authority of Electricity Regulation in Oman [61]. The EIA guidelines were used to establish the emissions both from oil and gas when used for electricity production. As per these guidelines, to produce 1 million British thermal units (btu) energy which is equal to 29.31 kWh from oil, a total of 161.30 pounds (=73.16 kg) of CO_2 is produced. Similarly, if the same amount of energy is produced from gas, then the total emissions will be equal to 117.0 pounds (53.07 kg). The emissions from electricity production in Oman considering both oil and gas are therefore calculated as follows:

Emissions from oil: Electricity produced from oil = total electricity consumption × percentage produced from oil = 70,633.37 million kWh × 70% = 49,443.35 million kWh per year.

Emissions for 29.31 kWh from oil = 73.16 kg CO_2.

Emission for 49,443.35 million kWh = $\frac{49{,}443.35\, x\, 73.16}{29.31}$ = 1.234×10^{11} kg = **123.414 million tons CO_2 per year.**

Emission from gas: Electricity produced from oil = total electricity consumption × percentage produced from oil = 70,633.37 million kWh × 30% = 21,190.01 million kWh per year.

Emissions for 29.31 kWh from gas = 53.07 kg CO_2.

Emission for 21,190.01 million kWh = $\frac{21{,}190.01\, x\, 53.07}{29.31}$ = 3.836×10^{10} kg = **38.367 million tons CO_2 per year.**

Total Emission from Electricity Production in Oman = 123.414 + 38.367 = 161.781 million tons CO_2 per year.

Overall, the emission from MSW and electricity production in Oman is therefore equal to 165.205 million tons CO_2 per year.

The next section presents different parameters of energy production from MSW in Oman.

4.4 Energy production from MSW

The composition of MSW presented in **Figure 6** shows that more than 50% of the MSW can be classified as combustible materials suitable for use in waste-to-energy plants. This indicates that a total of 1,079,610 tons per year (~3000 tons per day) of MSW can be used in waste-to-energy plants. The United States Energy Information Administration statistics indicate that 85% of the MSW can be burned in a waste-to-energy plant to produce electricity. Similarly, in some cases, the segregations of the waste are also not required as some of the latest plants known as the mass-burn waste-to-energy plant can process all the waste together. As shown in **Figure 7**, such plants have the capacity to segregates the waste such as metals, ash. The pant can also segregate the food waste and other organic waste that can be used in landfilling or for composting. Similarly, the separated ash can also be used as aggregates in construction works. These plants can also be classified based on their daily capacity. After reviewing the total waste-to-energy plants manufactured and installed by Deltaway Energy, these plants are found to have a capacity from 68 tons per day to 4900 tons per day [62]. To ensure a realistic estimate for the waste-to-energy plant, the MSW produced in different governorates were considered. As noted in **Table 2**, Muscat governorate, which is also the capital of Oman, is on the top of the waste production having a waste production capacity of 1905 tons per day. If Muscat, North AlBatinah, Al-Dakhiliya, South AlBatinah, South AlSharqiya, North AlShariqiya, and Al-Dhahirah governorates which are somehow close to each other (as shown in **Figure 8**) are considered, then the total production of waste will be equal to 5000 tons per day. Of course, these are 2017 data, and the population

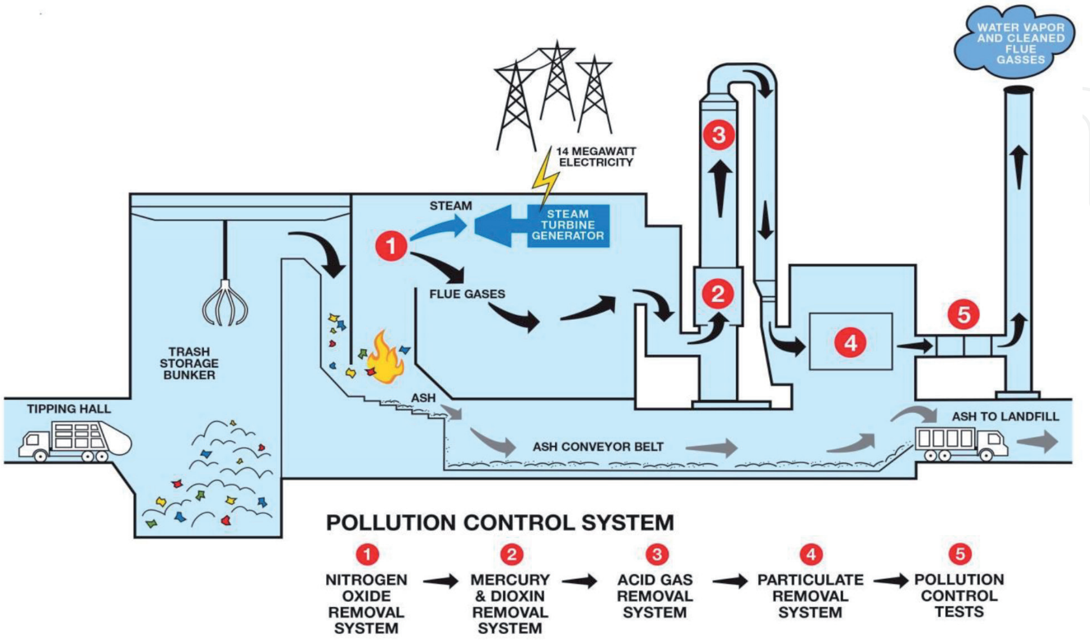

Figure 7.
A typical waste-to-energy plant.

Governorates	Waste production ton per year (2017)	Waste production ton per day (2017)
Muscat	685,654	1905
North AlBatinah	336,791	936
Al-Dakhiliya	330,185	917
Dhofar	330,884	919
South AlBatinah	150,038	417
South AlSharqiya	98,372	273
North AlShariqiya	98,372	273
Al-Dhahirah	106,055	295
Al-Buraiymi	154,374	429
Al-Wusta	9799	27

Table 2.
Waste generation in different governorates of Oman [63].

of these governorates will increase, the MSW production in these governorates will also increase. For instance, based on World Bank statistics, Oman's population increased at a rate of 3.4% per year [64]. Based on this indicator, the 2020 waste production in different governorates can be calculated using Eq. (3).

$$MSW_{(\text{future})} = MSW_{(\text{Current})} \text{ x} \left(1+\text{i}\right)^{\text{n}} \quad (3)$$

where $\text{MSW}_{(\text{future})}$ = the MSW generation in future (for instance in 2020) for Muscat governorate, $\text{MSW}_{(\text{Current})}$ = the MSW generation in future (for instance in 2017) for Muscat governorate, i = annual growth rate (decimal)—in this case, it can be 0.034, and n = number of years projected into future—in this case, it will be 3 years.

Based on the above parameters and using the equation, the Muscat governorate MSW production in 2020 will be 757,996 tons per year, which was 685,654 tons per year in 2017.

As noted in Section 3, 1 ton of MSW in the United States has the potential to produce 586 kWh, thus 5000 tons daily capacity waste-to-energy plant will be able to produce 29.30 million kWh daily. Similarly, this will help to reduce the volume of the waste that directly goes to landfills and produce emissions. Considering different parameters, the reduction of emissions through waste-to-energy plant is calculated below:

a. CO_2 emissions from 29.30 million kWh per day when produced by oil considering emissions for 1 kWh from oil = 2.5 kg CO_2 = 29.30 × 2.5 = **73.25 million kg CO_2 = 26,370 million kg CO_2 per year.**

b. Emission from 29.30 million kWh per day when produced by waste-to-energy plant considering 0.175 kg CO_2 per kWh [59] = 29.30 × 0.175 = **5.12 million kg CO_2 per day** = **1845.90 million kg CO_2 per year.**

c. Reduction of waste emissions from landfilling, considering a reduction of 1 ton per ton of MSW.

Figure 8.
Oman map showing different governorates.

Emissions per tons of MSW when disposed in landfilling = 1.58 ton per year CO_2 equivalent per ton of MSW.

Reduction in emissions per tons = 1.58 − 1.0 = 0.58 ton CO_2 per year.

Emissions from 5000 tons per year = 5000 × 0.58 = **2900 tons CO_2 per year** = **2.9 million kg CO_2 per year.**

Total reduction in emissions = **A – B + C = 26,370 − 1845.90 + 2.90 = 24,527 million kg CO_2 per year.**

Apart from the environmental performance of waste-to-energy plants, initial cost, operational cost, and return on investment are the key factors that the government or the investors considered in their decision. The initial cost of a waste-to-energy plant can be established considering its daily waste capacity. The Waste-to-Energy Research and Technology Council (WTERTC) has established the initial cost of a waste-to-energy plant at a rate of US$200,000 per daily ton of capacity. As the plant considered in the research has a capacity of 5000 tons per day, thus the initial cost of the plant can be estimated at US$1000 million [65]. Similarly, a 1000 ton daily capacity of the plant would require a total of 60 personnel, thus at this rate, a 5000 ton daily capacity plant would be able to generate employment for 300 workers. The operating costs of waste-to-energy plants in China are calculated at approximately US$30 per tons [66]. Depending on the life span of the plant, the operation cost can be up to 85% of the plants' total costs. If the plant has an estimated life of 40 years, then the cost of supply and construction can be 14% and the management and feasibility cost can be up to 1% of the total costs of the plant [67]. The research conducted by Carneiro and Gomes [68] established a levelized cost of electricity production from waste-to-energy plant at US$64–89 per MWh. Similarly, the profit margin of a waste-to-energy plant can be up to 25% while the return on investment can be up to 18%. The payback period of such a plant is normally 13 years with an internal rate of return up to 11% [66]. The research conducted by Kaplan et al. [69] in the United States estimated the average cost of electricity production from MSW at a rate of four cents per kWh with average revenue of US$25 per tons of MSW used in a waste-to-energy plant.

The next section provides a discussion and conclusion of the research.

5. Discussion and conclusion

It is been now well recognized that the earth resources need to be utilized in a sustainable manner as there is no other plant to live in. The UN SDGs and the Paris Agreements are some of the main indicators which reflect the commitment of world leaders toward sustainability. The main sustainability indicators such as energy and wastes are recognized so importantly that they have been placed among the 17 goals that the UN aims to achieve by 2030. The access to clean and modern energy does not mean that the people on the earth should be able to cook their food with gas or electric oven rather than burning the wood. This is one of the aspects, but the scope of clean energy is quite vast. It is not only to ensure access to clean and affordable energy but also to ensure the sustainability of such energy. For instance, making energy from fossil fuel is not sustainable because of two reasons. First, fossil fuels are not guaranteed to be available forever, and second, the emissions produced by such resources have other negative impacts that cause climate change and global warming. Even though, there is still doubt among the society that an increase of 1°C in the earth temperature is not a big issue. But in reality, such an increase creates a big difference by melting the glacier in the north and south poles. Such melting of glaciers not only expands the sea and but also disturbs the natural distribution of the dry and water portions on the earth's surface. The change in the natural distribution of wet and dry portions on the earth can cause the load variations on the earth plates which can increase the earthquakes. Apart from this phenomenon, the glacier on the earth's surface helps to reduce the temperature of the lower plates of the earth and thus reduce the chances of volcanic actions. It is therefore important to move toward renewable and sustainable resources for energy. Globally, some countries have reflected good progress in adopting renewable and sustainable energy resources, but in other countries including the GCC region, such progress is quite low.

Similarly, the UN under its Goal 12, which is related to the consumption of earth resources and production, aims to minimize the effect of such consumption and production. The waste produced during consumption and production has somehow similar effects as fossil fuels have. Such waste, if not properly disposed and recycled, will produce emissions and will utilize a large area on the earth's surface that can be used for some other purposes. Currently, the waste produced per capita in different countries is not only non-sustainable, but in most countries, there is no proper arrangement of recycling of such waste. In this regard, the GCC countries not only produce the highest amount of waste per capita (~1.77 kg per capita per day), but in most of these countries, landfilling is the common practice to dispose such waste. In all GCC countries, there is only one waste-to-energy plant in Qatar which has a capacity of 2300 tons per day, while the productions of MSW in all GCC countries currently stand at 93,430 tons per day.

This chapter, therefore, attempted to present a comparative study by considering the electricity production from waste-to-energy plants, considering the current electricity production and MSW generation. Both qualitative and quantitative research methods were utilized to achieve the aims and objectives of this research. The samples of the MSW collected from different entities including residential houses, shopping markets, hotels, and restaurants indicate a good volume (~50%) of combustible waste that can be used in a waste-to-energy plant. More than 70% of the interviewees confirmed that they are willing to segregate their MSW. The results further show that the current MSW generation in Oman stands at 1.3 ± 0.28 kg/per capita. This value and the current population of Oman are used to determine the total daily MSW generation in Oman. Since landfilling is used to dispose the total waste in Oman, the IPCC and ABC EIM guidelines were used to estimate the emissions from the total MSW. These calculations indicate the emission of 3,424,247 tons CO_2/year or 1.58 tons CO_2 per year per ton of MSW. Currently, Oman is producing 70% of electricity from oil and 30% from natural gas. The emissions from current electricity consumption (~70,633.37 million kWh per year) is estimated at 161.781 million tons CO_2 per year. If the emissions from the MSW are also added to this emission, then the total emission from electricity consumption and MSW generation in Oman will be equal to 165.205 million tons CO_2 per year. Considering the current energy consumption, MSW generation, and emissions from these variables, a waste-to-energy plant that has a capacity of 5000 tons per day is proposed to use the waste from Muscat, North AlBatinah, Al-Dakhiliya, South AlBatinah, South AlSharqiya, North AlShariqiya, and Al-Dhahirah governorates. Apart from producing 29.30 million kWh daily, this plant will be able to significantly reduce the emissions from the MSW and electricity production in Oman. The reduction in emission from this waste-to-energy plant is estimated at 24,527 million kg CO_2 per year. Similarly, this plant will be able to provide jobs for at least 300 personnel. The literature review suggests that the initial costs of such a plant with a capacity of 5000 tons per day can be equal to the US$1000 million. Similarly, the operating costs can be up to the US$30 per tons of waste used in the plant. Currently, the progress of Oman toward a number of UN SDGs is not satisfactory. Such an initiative of waste-to-energy plants will help Oman to improve its performance in a number of areas, including energy, climate change, waste management, and economic growth.

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