Frameworks for Reducing Greenhouse Gas (GHG) Emissions from Municipal Solid Waste in Oman

Structured Abstract:

Purpose (mandatory):

The Gulf Cooperation Council member countries not only generate the highest quantity of municipal solid waste per capita when compared globally but also in most of these countries such waste is just dumped at different landfill stations. In Oman, the total quantity of municipal solid waste stood at 2.0 million tonnes per year. The emission from this waste is estimated at 2,181,034 tonnes/year (carbon dioxide equivalent). This article attempts to develop frameworks that considered landfilling, composting and recycling of municipal solid waste.

Design/methodology/approach (mandatory):

To know the composition of the Municipal Solid Waste, in Oman, a quantitative research method was employed. The GHG emissions from MSWM in this study focus on three major gases, CO_2, CH4, and N_2O. The Intergovernmental Panel on Climate Change (IPCC) 2006 model is used to calculate GHG emissions from landfills and composting (IPCC, 2006). Four frameworks entitled baseline (F0), framework (F1), framework (F2), and framework (F3) are outlined proposed in this paper. The F0 represents the current situation of the MSW in which most of the waste goes to landfills and dumpsites. In F1 improved MSW collection service and landfilling are incorporated and open burning is restricted. The F2 considered landfilling and composting while F3 is based on landfilling, composting, and recycling.

Findings (mandatory):

The framework (F2) which proposes the composting process for the organic waste which normally goes to landfills results in the reduction of emissions by 40% as compared to landfill practice. Similarly, the samples of municipal solid waste collected in Oman show a good amount of recycling waste. The framework (F3) which considers the landfill, composting and recycling reduced the total Greenhouse Gas emissions from 2,181,034 tonnes/year to 1,427,998 tonnes/year (carbon dioxide equivalent); representing a total reduction of 35% in emissions.

Research limitations/implications (if applicable):

Different values such as CH4 correction factor, the fraction of degradable organic carbon, and the fraction of DOC used to determine the GHG emissions from MSW considering landfilling, composting and recycling are based on the IPPC model and existing literature review. The actual determination of these values based on the Oman conditions may result in more accurate emissions from MSW in Oman.

Practical implications (if applicable):

Different frameworks suggested in this research have different practical implications; however, the final framework (F3) which produces fewer emissions required a material recovery facility to recycle the MSW in Oman.

Social implications (if applicable):

For framework (F3), it important that the residents in Oman have enough knowledge and willingness to do the waste segregation at the household level. Apparently, such knowledge and willingness need to be determined through a separate study.

Originality/value (mandatory):

The frameworks F2 and F3 are considered to be more suitable solutions compared to the current practices for Oman and other gulf countries to reduce its per capita emissions from municipal solid waste and protect its local environment. There is a potential for further work that needs to explore the possible solutions to implement the suggested frameworks.

Unstructured Abstract:

The Gulf Cooperation Council member countries not only generate the highest quantity of municipal solid waste per capita when compared globally but also in most of these countries such waste is just dumped at different landfill stations. In Oman, the total quantity of municipal solid waste stood at 2.0 million tonnes/year. The emission from this waste is estimated at 2,181,034 tonnes/year (carbon dioxide equivalent). This article attempts to develop frameworks that considered landfilling, composting and recycling of municipal solid waste (MSW). The composition of the MSW is determined through a quantitative approach using 772 samples from houses, restaurants, and shopping markets. The Intergovernmental Panel on Climate Change guidelines were used to calculate the emissions from landfills and composting. The Atmospheric Brown Clouds Emission Inventory Manual (ABC EIM) is used to determine the emissions from open burning. The framework (F2) which proposes the composting process for the organic waste which normally goes to landfills results in the reduction of emissions by 40% as compared to landfill practice. Similarly, the samples of municipal solid waste collected in Oman show a good amount of recycling waste. The framework (F3) which considers the landfill, composting and recycling reduced the total emissions from 2,181,034 tonnes/year to 1,427,998 tonnes/year (carbon dioxide equivalent); representing a total reduction of 35% in emissions. The frameworks F2 and F3 are considered to be more suitable solutions compared to the current practices for Oman and other gulf countries to reduce its per capita emissions from MSW and protect its local environment.

Key Words: Municipal Solid Waste, Sustainability, Environment, Waste management & disposal, Emissions, Recycling.

1. Introduction:

The approach of 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 (Sachs, 2015). The need for sustainable development is truly recognized by all countries and thus in 2015; the United Nations was able to introduce seventeen Sustainable Development Goals (SDGs) to be achieved by 2030 (UN-SDG, 2015). The United Nations under Goal 12 (Responsible Consumption and Production) of its Sustainable Development Goals 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 municipal solid waste (MSW) generated is collected. The results of a current research conclude that extensive resources consumption and high amount of waste production is r one of the main factor which drive China’s urbanization away from sustainability (Fang et al., 2018). Appropriate waste management is therefore important for conserving local and global environments. In this regard, some studies reported that GHG emissions from the waste sector contribute 3-4% of total global GHG emissions (IPCC, 2007). The rapidly increasing amount of MSW in urban cities around the world is correlated with economic development as the increasing urban population is a major challenge that causes environmental degradation (Chen et al., 2010; Raheem and Ogebe, 2017).

The Gulf Cooperation Council (GCC) member countries (Saudi Arabia, Oman, United Arab Emirates, Kuwait, and Qatar) are considered as a major consumer of the natural resources which results into a huge amount of GHG emissions (Umar and Wamuziri, 2016; Umar and Egbu, 2018-a). Many studies have established that there is a great potential in a number of areas in the GCC region where renewable resources can be adopted in order to reduce the environmental impacts, however, the progress towards this is quite slow (Umar, 2017-a; Umar, 2017-b). Similarly, the annual solid waste generation in the GCC region has exceeded 150 million tonnes. The recycling of waste in the GCC is almost zero. The GCC countries featuring among the world's top ten in terms of per capita waste generation. One of the reasons for the high amount of solid waste generation in the region is the current boom of a number of industries including construction. The construction industry in all the GCC countries is at peak now as the region is on the way to improve its infrastructures, thus the construction sector is considered one of the main contributors to the solid waste generation in this region (Umar, 2016; Umar and Wamuziri, 2017). The global average waste generation per capita per day is 0.74 kg however the GCC average stands at 2.12 kg per capita per day (WB, 2019). The study conducted by Nnaji (2015) reported the MSW generated in Nigeria to be very low ranging from 0.13 kg/capita/day to 0.71 kg/capita/day. Lack of legal and institutional frameworks in GCC has been a major stumbling block in the progress of the waste management sector (Zafar, 2018-a). 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 (Zyoud et al., 2015).

Some recent studies which considered situations of waste in the whole gulf region indicate that the recycling sector is underdeveloped and hardly 10–15 percent of the waste is recycled (Zafar, 2015). This article considers the MSW in Oman which is currently deposited in some 350 landfills/dumpsites managed by municipalities. In Oman, most of the landfill areas are managed by the local municipalities. Four of the major landfill stations are managed by the Oman Holding Company for Environment Services SAOC (Be'ah). In Oman, most of the dumpsites are unauthorized or not managed by the local municipalities; however, at certain intervals municipalities removed wastes from these areas and put it to the landfill.

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. A survey conducted by the Oman Holding Company for Environment Services SAOC (Be'ah), 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%) (Be'ah, 2013). Apparently, this solid waste is not purely MSW and may include the industrial and commercial sources of waste. Some of the newspaper reports show that currently all of the MSW goes to dumpsites and landfills (Muscat Daily, 2017, Zafar, 2018-b). This research aims to estimate the GHG emissions from the current situation of MSW management in Oman as well as propose alternative solutions to reduce GHG emissions and environmental impacts.

The next section describes the relevant literature review that focuses on the MSW generation, MSW compositions, and the GHG emissions from MSW.

2. Literature Review:

As the population on the earth is gradually increasing, the future resources requirement could be huge to meet the human need. Kibert (2016) estimated that if all 7.3 billion of Earth's people consumed at the same rate as the average American, it would take six planets to support them. Since the population of Oman is also gradually increasing, the waste generation is expected to research to 1.96 Million tons per year by 2040. This value was 1.19 million tons per year in 2010, which means that each year, the waste generation in Oman is increasing at a rate of 2.03%. Both the Omani Vision 2020 and 2040 stressed to reduce the dependency on natural resources; however, the country's progress to achieve their vision goals is slow (SCP, 1995; SCP, 2019).

Currently, in Oman, all the waste generated is dumped in more than 300 dumpsites located in different parts of the country. Different governorates generate different amounts of MSW, but on average it is equal to 1.2 Kg per capita per day. In any case, the quantity of the MSW in Oman is too high, particularly in the current situation when all the waste is disposed of at dumpsites. Such dumping of the waste not only occupies a large area of the land but also creates environmental and climate change issues. Due to the high level of natural resources consumption, the average CO_2 emission per capita is GCC countries including Oman is (= 25.36 Tonne) is three times greater than the CO_2 emission per capita in China (= 7.5 tonne) and almost four times greater than the CO_2 emission per capita in United Kingdom (= 6.5 tonne) (WB, 2014).

While there are a variety of ways to reduce this emission, reduction in waste and recycling is one of them (Pongpimol et al., 2020). In fact, there are some studies conducted in Oman which explore the potential of energy production from waste which has a high amount of biomass (Umar, 2018). Although, the quantity of MSW generation in Oman (1.28 Kg/capita/day) is low compared to other GCC countries (~1.5 Kg/capita/day), however the plastic content in the MSW is approximately the same. A recent study conducted by Hahladakis and Aljabri (2019) on MSW in Qatar concluded that plastic waste is equal to 13-14% of the total waste generated in Qatar. Waste such as metals, paper, glass, and plastics are materials considered of high recyclable potential which could enable a circular way of management, therefore there is an opportunity for Oman to consider the recycling of MSW to avoid environmental impact (European Commission, 2016).

The progress of Oman towards UN SDGs is comparatively low. For instance, the Sustainable Development Report (SDGIDR, 2018) for the year 2018 ranked Oman 94 out of 156 countries based on their progress towards these goals. At the same time the United Arab Emirates, which a close neighbor country of Oman in the GCC region is ranked 60 out of 156 countries. The United Arab Emirates, therefore, represents better progress than Oman towards UN SDGs (Umar et al., 2020). The report further indicates that there are major challenges for Oman to achieve the Goal: 12 (Responsible consumption and production) and Goal: 13 (Climate action) by 2030. Sustainable disposal and recycling of MSW in Oman could be helpful to protect the local environment but will also be helpful to achieve related UN Sustainable development Goals and improve its sustainable ranking worldwide.

The composition of the MSW is normally determined through sampling from different units that include residential houses, restaurants, shopping markets, and hotels. These units were used for sampling to know the composition of MSW in different studies including Otoma et al. (2013). In Oman, the municipalities are responsible to collect and dispose of the waste generated by residential houses, restaurants, shopping markets, and hotels. Apart from the statistical significance of the sample, many studies reflect that the nature of the study significantly affects the sample size of the study (Umar et al., 2018; Umar and Egbu, 2020). Likewise, the family size also needed to be considered in the selection of the participants. A UN report indicates that Oman is one of the largest countries in terms of the household size where the average household size is greater than five (UN, 2017). Another report from Esri indicates that the average household size in Oman is 6.9 people per household (Esri, 2019). Thus it is important that the sample size used in such a study should consider the Omani household size.

One of the methods which are commonly used to know the segregation of the MSW was developed by the Japan International Cooperation Agency (JICA). Based on this method, MSW can be segregated into three main components including Organic, Inorganic, and recyclable MSW. As per JICA guidelines, different items in the MSW that can be classified as organic or inorganic waste.

GHG emissions from MSW are normally composed of the three main gases including, CO_2, CH_4, and N_2O (Du et al., 2017). Many researchers used the Intergovernmental Panel on Climate Change (IPCC, 2006) to estimate GHG emissions from landfills and composting (Syeda et al, 2017; Babel and Vilaysouk, 2016; IPCC, 2006). Similarly, the IPCC model is also adopted by the United Nations Framework Convention on Climate Change (UNFCCC) member countries to report their country GHG emissions (UNFCCC, 2014). In case the historical statistics of MSW which is needed for a higher tier, the IPCC model recommends using the default method for emissions (Ramachandra et al., 2018). Tier 1 employs the gain-loss approach mentioned in the IPCC Guidelines and the default emission factors and relevant specifications are provided by the IPCC (Singh and Basak, 2018). This method is considered suitable for

Oman as the historical data related to MSW is either not available or difficult to obtain. To know the emissions from different methods of MSW disposals in Oman would be helpful to adopt the one which produces less emission.

The Oman total population as of May 2019 was 4,689,522 (NCSI, 2019). Overall 45% of the residents in Oman are expatriates and the majority of them belong to some Asian countries (Umar, 2016). The participants in the data collection in the quantitative or qualitative study are therefore needed to be selected in a way so that there could be no communication barriers. Overall, the existing literature review suggests that the composition of the MSW is important in order to estimate the GHG emissions from such waste and develop strategies to reduce such emissions. There is, however, no study in this area in Oman.

The research methodology adopted to achieve the aims and objectives of this research is explained in the next section.

3. Research Methodology:

The research was conducted in two main stages. In the first stage, the composition of the MSW in Oman was determined. In the second stage, the GHG emissions were estimated considering the current disposal methods and proposing the new frameworks. To know the composition of the Municipal Solid Waste, in Oman, a quantitative research method described by Umar and Egbu (2018-b) was employed. A total of 772 samples collected from 90 residential houses, six restaurants, and four shopping markets. The houses were selected in a way so that the reliability both in terms of their participation and statistical significant could be achieved. A sample of 87 respondents was considered statistically significant in a study related to the challenges towards renewable energy in GCC countries conducted by Umar et al., (2019-a). The review of existing literature, however, suggests that similar studies can also be carried out with a much smaller sample size. As discussed in the literature review section, the household size in Oman is comparatively large, thus, the houses with the family member of 4, 5, 6, 7 and 8 were considered for data collection. 18 samples of waste were collected from each house on a 24 hours basis. Six samples were collected from six different restaurants and four samples were collected from four shopping markets. The samples were deposed in the municipality collection point after recording the required data.

The GHG emissions from MSW in this study focus on three major gases, CO_2, CH_4, and N_2O. The IPCC (2006) model is used to calculate GHG emissions from landfills and composting (IPCC, 2006). IPCC model is an international model used by The UNFCCC member countries to report the national GHG inventory. In this research, IPCC (2006) is used to determine only GHG emissions from landfills and composting. Due to the unavailability of historical data on MSW which is required for a higher Tier, the Tier 1 (default method) is used to determine GHG emissions from landfills and composting. Equation 1 is used to calculate the CH_4 emission from landfills. Tier 1 employs the gain-loss approach mentioned in the IPCC Guidelines and the default emission factors and other parameters provided by the IPCC. There may be simplifying assumptions about some carbon pools. It, however, needs to be noted that that as a result of the uncertainties, the calculations are only approximate but still useful as a guide to the likely scale of impacts.

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

……………..Equation 1

Where,

CH_4 = Methane Emission in Gg/year (1 Gg = 10^9 g; 1 Gg = 1,000 tonne)

$MSW_{(Land\ Fill)}$ = total amount of MSW in the landfill in wet weight basis (Gg/year)

MCF = CH_4 correction factor

DOC = the fraction of degradable organic carbon in MSW (Gg C/Gg MSW)

DOC_f = the fraction of DOC that can decompose (fraction)

F = the fraction of CH_4 in generated landfill gas

R = the recovered CH4 (Gg/year), 16/12 is the molecular weight ratio CH_4/C

OX = the oxidation factor

For the calculation of GHG emissions from landfills in this research, some parameters are based on the default data of the model. According to the field observations, the depth of landfills in Oman varies and does not fit into either managed or unmanaged landfill accordingly to IPCC criteria. Thus, the landfill type selected in this research is uncategorized landfill and MCF of 0.6, based on default values provided is used. DOC is calculated separately, taking into account the MSW composition and the fraction of degradable organic carbon in each component. The DOC depends on the composition of deposited waste at the landfill in each scenario. The actual DOC on a wet weight basis of the waste disposed on the landfill in each scenario is used for the estimation. DOC_f depends on number factors including temperature, moisture, pH, and waste composition. IPCC (2006) recommended DOC_f values between 0.42 – 0.77. A value of 0.77 was used in several studies (Kumar et al., 2004; Jha et al., 2008; Aguilar-Virgen et al., 2014; Babel and Vilaysouk, 2016; Vilaysouk and Babel, 2017). Although the IPCC values for the DOC_f range from 0.4 to 0.77, the default value set by the IPCC is 0.77. The main waste element that is disposed of in landfills generates approximately 50% of CH_4, and thus, F is 0.5 in this research. Since there was no energy recovery or landfill gas collection system, so R equals zero is used for estimation. The OX parameter indicates the amount of CH_4 that oxidizes in the cover layer of landfill; OX is selected as zero, as the dumpsites in this research are considered as unmanaged dumpsites. As discussed earlier, there are only four landfill sites in Oman that are managed by the

Oman Holding Company for Environment Services SAOC (Be’ah). In fact, the actual value for the OX needs to be determined considering the Oman waste composition and climatic condition. It needs to be noted that if the value of OX increases the GHG emissions will change (Leeand Wang, 2017).

For composting, the generation rates of both CH_4 and N_2O depend on many factors including the amount of degradable material, temperature, moisture content, and the aeration. The CH_4 and N_2O emissions from the composting scenario in this research are estimated using equation 2 as under.

$EM = (M \times EF) \times 10^{-3} - R$ …………… Equation 2

Where;

EM = GHG emissions from composting (Gg/year)

M = amount of MSW composted (Gg/year)

EF = an emission factor (g/kg waste)

R = amount of methane recovery (Gg/year)

For comparing results for different gas species in this study, CH_4 and N_2O emission are converted to carbon dioxide equivalents (CO_2-eq) on a 100-year time horizon basis. The multiplication factors of 21 and 310, based on a mass basis (Houghton, 1996), are used for CH_4 and N_2O, respectively. Open burning of the waste is a source of CO_2, CH_4, sulfur dioxide, nitrogen oxides, particulate matter, non-methane volatile organic compound, ammonia, and black carbon. The ABC EIM is developed specifically for the calculation of air pollution in Asian countries from biomass open burning (Shrestha et al., 2013). Thus it is used to estimate CH_4 and CO_2 emission in this research, as the emission factors used for calculation are based on the Asian countries, which is more relevant to Oman rather than IPCC that uses global emission factors. Permadi and Oanh (2013) also tested ABC EIM to calculate air pollution from biomass open burning in Indonesia. CO_2 and CH_4 emissions from open burning in this research are calculated by using the general equation from Shrestha et al., (2013) study (Equation 3).

$EM_i = MSW_{OB} \times \delta \times \eta \times 365 \times EF_i$ ……………..Equation 3

where,

EM_i = the emission of pollutant i (tonnes/year)

MSW_{OB} = the amount of MSW open burned (Gg/day)

δ = the fraction of combustible waste (fraction)

η = the burning/oxidation efficiency (fraction)

365 = day/year

EF_i = the emission factor of pollutant i (tonnes/Gg)

MSW_{OB} can be roughly calculated by the multiplication of waste generation, population, and the fraction of residents burning the waste (Shrestha et al., 2013). Nearly 20% of the total waste generated in Thailand is open burned (Permadi and Oanh, 2013). Karak et al. (2012) reported that in low-income countries, open burning is practiced to reduce the volume and odor of uncollected waste, such as by 25% and 15% for Burkina Faso and Nepal, respectively. There are many studies reporting the practice of employing open burning of MSW (Forbid et al., 2011; Seng et al., 2011; Karak et al., 2012; Otoma et al., 2013; Thanh and Matsui, 2013

The uncollected waste (mostly from the suburban area) is disposed of mainly by open burning and illegal dumping in Oman. This accounts for 41% of total waste generated in some countries (Cogut, 2016). For instance, a study conducted by Wiedinmyer et al., (2014) considering 226 countries including Oman reported that a total of 26% of the residential waste is normally open burned in these countries. In accordance with some reference data mentioned above and from field observations, about 15% of total MSW generated is assumed by the authors for the fraction of open burning in Oman. The fraction of combustible material is based on MSW composition in Vientiane (Babel and Vilaysouk, 2016). The burning efficiency and emission factors are based on default values in ABC EIM.

To establish an applicable and suitable MSW management plan for dealing with waste in Oman, the characteristics of MSW, available and practiced technology, public participation, and the government policies, were taken into consideration. Reducing the amount of waste landfilled, introducing composting at source and recycling were included in the framework development. Framework F1 attempts to expand the MSW collection service, and the increased amount is assumed to be diverted to be disposed of in the landfill. The current situation of MSWM in Oman is represented in the baseline (F0). The framework (F1) attempts to expand MSW management collection services, and the increased amount of MSW from collection expansion is assumed to be disposed of in the existing managed landfills. The assumptions in the framework (F1) might lead to an increase in the total GHG emissions from the landfill; however, it will keep the environment clean and reduce the problems that might occur from open burning and illegal dumping. Composting was proposed in the framework (F2) for dealing with organic waste (food and garden waste). Recycling and the composting amount is increased in Framework (F3) in order to recover the materials, extend the lifespan of the landfills and to reduce GHG emissions. The detailed information about developed frameworks is shown in Table 1.

Table 1: MSW management Method in Each framework (tonnes/year)

4. Results and Analysis:

A total of 772 MSW samples were collected from different entities mentioned in section 2. The mean weight of the samples was 1.4 $\pm$ 0.3 kg. The analysis of these samples indicate food items (38%), paper/ cardboard (10%), textile (6%), rubber/ lather (5%), garden waste (17%), plastic (13%), glass (7%), metal (3%), and other / inert items (1%). The composition of the samples was almost the same as reported by the Japan International Cooperation Agency report on the "Laos Pilot Program for Narrowing the Development Gap towards ASEAN Integration" (JICA, 2012). The next sections describe the parameters and emissions from different methods of disposal considered in this research.

4.1. Baseline (F0):

As of 11th June 2019, the total population of Oman stood at 4,646,651 (NCSI, 2019). The estimated MSW generation in Oman was reported as 1.2 kg/capita/day. Thus the total MSW generation in Oman is estimated at 2.0 million tonnes per year. It is estimated that the total quantity of the collected MSW in 2019 will be 1.83 Million tonnes (Be'ah, 2016). Currently, there are no recycling facilities for MSW in Oman, all the collected waste in Oman is dumped in landfills and dumpsites. The majority of the dumpsites are uncontrolled thus the chances of open burning are possible. Considering this situation, 15% of the total MSW collected or disposed of at the dumpsites in Oman is considered for open burning. Thus the amount of waste for landfills and dumpsites is reduced to 1,555,500 tonnes/ year and open burning stands at 274,500 tonnes/ years. The total quantity for open burning in the baseline, therefore, stands at 274,500 tonnes/ year (table 1). The difference between the total MSW and the waste used in open burning and landfill is thus categories as uncontrolled which is equal to 177,353 tonnes/ year [(2,007,353 (-) 1,555,500 (-) 274,500 = 177,353). This uncollected waste will have some emissions based on the methods in which this waste is disposed. Since these methods were unknown, the emissions from this waste are assumed to be similar to the emissions from the landfills and dumpsites. Such emissions are roughly equal to 198,998 tonnes/year CO_2-eq, provided that this waste goes to dumpsites and landfills.

The calculation shows that the total CH_4 emission from landfills and dumpsites in Oman is 1,745,341 tonnes/year CO_2-eq. The results of the baseline (F0) show that total CO_2 emission from open burning is 216,369 tonnes/year CO_2-eq and CH_4 is 20,326 tonnes/year CO_2-eq. However, if biogenic CO_2 emission (plants and animal materials) and is considered to be 50% of total CO_2 emission, as reported in many studies (Larsen et al., 2013; Babel and Vilaysouk, 2016), the total CO_2 emission from open burning would be 108,184 tonnes/year CO_2-eq. The total GHG emissions from the current situation of MSW in Oman, including the assumption of open burning, is 2,181,034 tonnes/year CO_2-eq. The total CH_4 from landfills accounts for 90% of total GHG emissions in this framework. Numerous problems exist along with the uncollected MSW amount. Improvement of MSW collection service is one of the alternative options in order to handle the uncollected amount as well as reducing the amount of open burning.

4.2. Framework (F1): Improved MSW Collection Service and Landfilling:

This framework is developed to protect the environment by increasing the MSW collection service and to reduce illegal dumping and open burning. Both the Omani visions 2020 and 2040 stress on the action plans that improve MSW collection service and emphasize that improved MSW collection system is mandatory to reduce the impact on the natural environment (SCP, 1995; SCP, 2019). Thus, from the total uncollected MSW mentioned in the baseline (F0), 60% is diverted to the landfill in this framework. Similarly, the open burning is to be restricted in this framework. As mentioned in table 1, the total MSW disposed of in the landfills is supposed to be 1,936,412 tonnes/year (83% of total MSW generated). Eventually, the uncollected amount is reduced from 177,353 tonnes/year to 70,941 tonnes/year (9% to 3.5% of total MSW generated). The emissions from the uncollected waste are roughly equal to 79,595 tonnes/year CO_2-eq. Although this may increase the total GHG emissions, both from increased landfill amount and GHG emissions by vehicles during MSW collection, it is a much better option and can reduce the number of unmanaged dumpsites. From the results, it can be seen that CH_4 emission from landfills has increased accordingly with the increasing amount of waste deposited in landfills. Total GHG emissions from this framework are 2,220,296 tonnes/year CO_2-eq.

4.3. Framework F2 (Landfilling and Composting):

Food waste, garden waste, and paper waste are accounted for approximately 64% of the total quantity of the MSW that goes to landfills and dumpsites in Oman. Composting is one of the alternative options for handling organic materials in MSW. Composting on a large scale requires effective source separation and transportation, which results in increased operational costs. To reduce such problematic financial burdens in the operation, a community composting center and home composting systems can be adopted (Adhikari et al., 2010). This framework aims to reduce the amount of MSW deposited on landfills by proposing composting at the household level. Such a composting process will require the motivations and willingness of the public. The composting at the source proposed in this study is also supported by the action plan for solid waste management in Oman in an Eco-Composting campaign that is currently practiced in some countries (Be'ah, 2016; JICA, 2012). Additionally, the compost produced from organic waste could be utilized to enhance agriculture activities as well as for soil amendment. Framework F2 is supposed to divert 50% of the total organic waste (food waste and garden waste) going to the landfills to the composting process. The total amount of waste that is handled by the composting is 968,206 tonnes/year (table 1). By introducing composting at the household level, the uncollected waste could be reduced relatively. The total GHG emission in this framework is to be 1,226,517 tonnes/year CO_2-eq.

4.4. Framework F3 (Landfilling, Composting, and Recycling):

Recycling plays an important role in reducing resource consumption as well as other input materials in the production process. Omani Vision 2020 and 2040 stress on protecting natural resources and recycling (SCP, 1995; SCP, 2019). Under these visions, the Government aims to adopt the waste management hierarchy that includes the main four-pillar including disposal, recycle, reuse and reduction. Recycling and reusing were also considered as important elements in achieving sustainability in higher education institutions (Umar, 2020). The samples of MSW collected in this research show paper, plastic, glass, and metal account for 33% of the total waste. Currently, none of these wastes are recycled in Oman.

Framework (F3) is developed to adopt the recycling of recyclable waste at households. Adopting a specific amount of recycling could reduce the amount of waste deposited in the landfill, thus, the lifespan of the landfills could be extended. Assuming that 50% of recyclable waste is separated at households, the total amount of recycling waste as noted in table 1 will be equal to 331,213 tonnes/year (16.5 % of total MSW generated). By proposing the recycling in this framework, the amount of the waste disposed on the landfills/dumpsites and uncollected waste is reduced. Total MSW disposed of in landfills is 636,993 tonnes/year, and the uncollected waste remains as 70,941 tonnes/year. The total GHG emissions from landfills in this framework are reduced to 757,852 tonnes/year CO_2-eq, and total GHG from composting is 171,373 tonnes/year.

Although the recycling of MSW does produce emissions that are presented in the next section, there are other environmental and social benefits associated with this option. The composting amount is unchanged in this framework and remains the same as noted in framework F2. The total GHG emission in this framework is reduced by 35% compared to the baseline (F0). This reduction is based on the recycling the MSW in a material recovery facility.

The common methods for recycling the MSW includes the waste to energy approach and material recovery method (Zsigraiova et al., 2009; Monni, 2012; Mohareb et al., 2008; Damgaard et al., 2010; Tchanche et al., 2011). Although these facilities of recycling the MSW do not exist in Oman, it is important to estimate the emissions from such activity presented in this framework (F3). 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 ((Braschel and Posch, 2013). Since such emissions were not considered in any of the frameworks presented in this study, it is ignored here as well while calculating the emissions from different types of recycling. Briefly, the GHG emission factor which accounts for MSW hauling can be 19.1 g CO_2-eq/tonne/km (DEFRA, 2011).

A good option for recycling the MSW is to use it in a material recovery facility. Currently, such a facility does not exist in Oman, however, it can be a good option to recycle some of the waste with lower emissions compared to waste-to-energy options. A small material recovery facility that has a capacity to handle less than 10 tons of MSW per day cost around US 1 Million and required an area of 1,400 sqm (Zafar, 2019). The material recovery capacity in the city of Sharjah of the United Arab Emirates with an annual capacity of 500,000 tonnes is the largest in the Middle East and ranks the third largest in the world (Beea'h-UAE, 2018). In a material recovery facility center, there are many processes involved with different types of equipment that generate GHG emissions while using diesel or electricity. Mostly, the material recovery facility uses 1.94 kWh electricity for handling one tonne of MSW, and the GHG emission generated from the electricity consumption is 0.521 kg CO_2-eq/kWh (Fisher, 2006; TEPA, 2015). Different studies have established the GHG emission from material recovery facilities which range from 0.047 to 4.448 kg CO_2-eq/tonne/day (Mohareb et al., 2008). A more recent study conducted by Chen and Lo (2016) has established these emissions as 1.01 kg CO_2-eq/tonne/day and this value has been used to estimate the emissions in this study considering the fact that this is a recent study and the value of GHG emission established by them is in the range of the values determined by Mohareb et al. (2008). The total value of the GHG emission considering the quantity of recycling the waste as 331,213 tonnes/year and the emission value as 0.368 tonnes CO_2-eq/tonne/year, is 121,886 tonnes CO_2-eq/tonne/year. The material recovery facility, therefore, produces much lower emissions than the waste-to-energy plant. The emissions from the material recovery facility are considered while comparing framework (F3) with other frameworks.

5. Discussion:

Oman similar to other developing countries particular to GCC countries relies on landfilling and dumping for MSW disposal. Most of the dumping station in Oman can be classified as unmanaged, thus, the degradation process is not completely anaerobic. The results of this study show that the emission factor (EF) is equal to 0.053 tonne CH_4/ tonne MSW. EF from landfills and dumpsites in Oman is higher than other studies that have used the IPCC model. For instance, the study by Jha et al. (2008) reported EF as 0.026 tonne CH_4/ tonne MSW. Similarly, Kumar et al. (2004) reported EF as 0.024 tonne CH_4/ tonne MSW. The quoted studies here are, however, from a different region (India), that doesn't have the same environmental conditions as of Oman. Thus the difference in EF is obvious, however, higher EF from Oman landfills is due to different amounts of organic material deposited on the landfills (reflect DOC value) and the classification of landfills or dumpsites type (based on MCF value).

Organic wastes, which are the main part of MSW in Oman, significantly contribute to the total amount of CH_4 emission from landfills in the framework (F1). Due to poorly managed landfills, coupled with the significant amount of GHG emissions, landfilling is still not a good option for MSW. Other alternative options for handling and disposal of MSW, therefore, need to be investigated.

CH_4 emission from landfills is the main contributor, but it is reduced due to the reduction of deposited amounts of MSW, especially food waste and garden waste which contain high DOC. Also, the diversion of organic waste to the composting process causes changes in DOC value. DOC is considered as one of the important parameters that influence the CH_4 generation rate in landfills. In this framework, the DOC value is decreased due to the reduction of high DOC fractions such as food waste and garden waste in the deposited waste. Even so, CH_4 emissions from landfills still account for 86% of CO_2-eq in this framework.

In this research, only CH_4 and N_2O are taken into consideration for composting. The results show that CH_4 emission from composting is relatively low compared to landfilling and is 81,335 tonnes/year CO_2-eq. N_2O is a major source of GHG emission in composting, contributing to 9,0038 tonnes/year CO2-eq. Total GHG emission from the framework (F2) has significantly changed. About 38.11% reduction is observed compared to the baseline (F0) and at the same time compost produced can be used for agricultural activities. From the results in the framework (F2), composting is a key factor for dealing with MSW that mostly contains organic material in terms of GHG emission reduction, as well as the prevention of waste to landfill.

The total GHG emissions in different frameworks vary from 1,427,998 tonnes/year to 2,220,296 tonnes/year CO_2-eq, which depend on the disposal method. The difference between baseline (F) and the framework (F1) is only 2%. In other words framework

(F1) produces 2% extra emissions compared to baseline (F0). The open burning in the framework (F1) is considered zero and all the MSW is directed to the landfill areas. In framework F1, it is assumed that all (100%) MSW is collected, thus the highest GHG emitter (= 2,220,296 tonnes/year CO_2-eq). In this framework, the CH_4 gas is a major source of emissions. Since baseline (F0) represents the current scenario of MSW in Oman, thus GHG emissions in this framework are used to compare with the other developed framework. Comparing the results from the framework (F1) with the baseline (F0), the GHG emission is increased by 2% because all generated waste now goes to landfills. The total GHG is significantly reduced in the framework (F2) by 40% when compared with baseline (F0) due to the reduction of organic waste at the landfill by composting. Additionally, framework (F3) is developed, taking into consideration the trend of MSWM with regards to government policies and visions. Framework (F3) includes recycling, composting at generation source, and landfilling as the last option. In terms of GHG emissions, framework F3 can achieve a 35% reduction of GHG emissions compared to baseline (F0). It, however, needs to be noted that these frameworks are developed based on certain assumptions and characteristics of the waste in Oman. If these assumptions or the composition of the waste change, the results mentioned in these frameworks would also change. Thus the results presented in this paper should be treated as indicative only.

5. Conclusion:

Many efforts around the world are underway to effectively manage and dispose of the MSW in a better way so that the associated environmental impacts can be reduced. There are varieties of solutions that can be adopted to reduce such emissions which not only protect the environment but can help countries to achieve the relevant SDGs. In this article, the GHG emissions from MSW in one of the GCC countries are outlined. Different frameworks that include landfilling, composting and recycling have been proposed to reduce the high amount of emission from MSW in the region. Considering the characteristics of MSW, government policy on MSW management and available technology, frameworks F2 and F3 are considered to be the most effective solution for Oman and other GCC countries to deal with MSW and to reduce GHG emissions, air pollution, protect its environment and maintain good progress towards relevant UN SDGs. It is also important to note that framework F3 which includes the recycling of 16.5 % of the total MSW generated in Oman also takes into account the emissions produces by the material recovery approach. Currently, there is no material recovery plant in Oman, adopting this option will require some investment, however, it will help the country not only to reduce the emissions from MSW but such facilities will create job opportunities and thus will contribute to the social and economic development of the country. The frameworks developed in this paper are based on some assumptions particularly related to the quantity of open burning in Oman. Similarly, in the estimation of GHG emissions, some values used in the calculations are based on the default values of the IPCC and ABC EIM. The actual estimation of the actual values associated with GHG emissions is therefore important to establish accurate emissions from MSW. Further research is recommended to first know the actual quantity of open burning and then to estimate the GHG from such burning. There is a potential for further work that needs to explore the possible solutions to implement the suggested frameworks.

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