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Quantification of Methane Emissions from Solid Waste in Oman Using IPCC Default Methodology

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***Abstract*—**Municipal Solid Waste (MSW) disposed in landfill sites decompose under anaerobic conditions and produce gases which mainly contain carbon dioxide (CO_2) and methane (CH_4). Methane has the potential of causing global warming 25 times more than CO_2, and can potentially affect human life and environment. Thus, this research aims to determine MSW generation and the annual CH_4 emissions from the generated waste in Oman over the years 1971-2030. The estimation of total waste generation was performed using existing models, while the CH_4 emissions estimation was performed using the intergovernmental panel on climate change (IPCC) default method. It is found that total MSW generation in Oman might be reached 3,089 Gg in the year 2030, which approximately produced 85 Gg of CH_4 emissions in the year 2030.

***Keywords*—**Methane, emissions, landfills, solid waste.

I. Introduction

THE generation of municipal solid waste (MSW) has rapidly increased worldwide due to the fast economic development and urbanization, which also significantly changed the composition of MSW. The greatest amounts of MSW across the world are generally produced by the gulf regions. The total volume of solid waste generated in gulf region is approximately 120 million tons per year, in which MSW is the second largest waste category by source [1]. Of all Gulf Cooperation Council (GCC) countries, Oman has made the most rapid progress in the development within a short period of time. The country today is very different from what it was in 1970 where Oman has built a modern infrastructure and the level of industrialization has increased markedly. Oman has one of the highest amount of waste generated per capita in the world, around 1.6 kg per day [2].

Disposal of MSW in landfills results in the generation of huge amounts of greenhouse gas (GHG) because the decomposition of MSW under anaerobic conditions produces landfill gas (LFG) containing approximately 50–60% methane (CH_4) and 30–40% carbon dioxide (CO_2) by volume. CH_4 has a global warming potential 25 times greater than CO_2, which has adverse effects on the environment. Migration of CH_4 gas from landfills to the surrounding environment can potentially affect human life. Gas explosion incidents were reported at Loscoe village in England at 1986, and Skellingsted Landfill in Denmark [3] due to CH_4 gas migration. The CH_4 emission from landfills is continually increasing due to increasing population growth and per capita waste generation, which caused landfills ranking as the third-largest anthropogenic CH_4 source after rice paddies and ruminants [4]. The Inter-governmental Panel on Climate Change (IPCC) estimated that CH4 landfill emissions account for approximately 12% of global CH4 emissions [5].

In past decades, methane (CH4) emission from landfills has usually been estimated using statistics on population and waste quality and quantity [6]; many models are currently available. The IPCC introduced three tiers for estimating CH4 emission from landfills in each country: Tier 1, Tier 2 and Tier 3. Tier 1 method is the default method and is based on a mass-balance approach to estimate total national emissions using a number of empirical constant parameters, e.g., the methane-correction factor (MCF), degradable organic compounds (DOC), and dissimilated organic fraction converted into landfill gas (LFG) (DOCf), considered while developing the default methodology [7]. Tier 2 and 3 methods are based on a first-order decay (FOD) in the emission calculations [8]. The decision of choosing the most appropriate method is based on the availability of current and historical country specific data on waste disposed of in landfills.

The current paper aims to determine MSW generation in Oman over the years 1971-2030, and quantify annual CH4 emissions inventory resulted from this waste over the same period of time. The estimation and prediction of MSW generation play an important role in MSW management in Oman. It is very important for the local authority in Oman to know how much solid waste is generated so that they can assess their current and future needs in budgeting, operation, and processing equipment. The study also important for conducting projects aim to capture CH4 gas from landfills and used it for electricity generation, and thereby provide a sustainable waste management solution.

II. Background Information

Sultanate of Oman is an Arab country located at the Southeast corner of Arabian Peninsula. It is located 23 60° North and 58 55° East coordinates. Oman's main city and capital is Muscat. The total population of Oman is 3.623 million according to the 2013 statistics. Oman shares its border with United Arab Emirates in North – West, Saudi

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Arabia in the West and Yemen in the South – West.

The regulation of managing MSW in Oman was issued by a ministerial decree number 17/93 stating that it is "any solid or sub solid matter that does not cause harm to the environment or human health if treated in the proper scientific ways" [9]. Currently, the waste management sector in Oman is in evolution stage. The operations for the management of solid waste (municipal and industrial) are performed by the municipalities. According to the Recommendations of the Draft National Solid Waste Management Strategy Report (former Ministry of National Economy), The Oman Environmental Services Holding Company (be'ah) S.A.O.C (OESH-CO) was officially established in July 2007 and later on according to the Royal Decree (46/2009) be'ah was officially entitled to take over the full responsibility of waste management in Oman [10]. This include waste collection, separation, transportation, recycling, land filling and handling of all hazardous and non-hazardous waste in the Sultanate. It is aimed to "moving Oman to zero waste, by providing safe, efficient and most economical environmental services in innovative ways". Currently, there are no waste treatment facilities, and dumping waste into landfills is the only and ultimate way of waste disposal.

III. Methods

A. Total Waste Generation

The scenario for estimation of MSW generation in this research was followed [11] method, which estimated annual per capita waste generation based on annual per capita energy consumption. Two liner regression models were provided by [11] for estimating per capita waste generation from per capita energy consumption. The first linear model was for developed countries with per capita energy consumption higher than 1500 Kg cool equivalent per year, while the second for developing countries with per capita energy consumption less than 1500 Kg cool equivalent per year. Therefore, annual per capita energy consumption in Oman from 1971 till 2011, and annual historic Oman population from 1971 till 2011 were collected and used with the models provided by [11] for developed and developing countries to estimate the annual per capita waste generation over the years 1971-2011. The results from both models were compared with existed values of annual per capita waste generation data in order to select the best fit model resulting in a minimum root mean square error (RMSE) value using (1). Finally, a model will be developed based on the estimated annual per capita waste generation data from 1971 till 2011 in order to predict the per capita annual waste generation from the year 2011 to 2030. Consequently, the annual per capita waste generation together with the annual population will be used to estimate total annual waste generation.

$$R = \sqrt{\frac{\sum_{i=1}^{n}(f(x_i)-y_i)^2}{n}} \quad (1)$$

where, $f(x_i)$ is the per capita waste generation collected from The Report: Oman 2012 Oxford Business Group in the year i, y_i is the amount of waste generation estimated using the models prepared for developed and developing countries for the year i and n is the number of years.

B. Methane Inventory from Waste Generation

The default methodology was used in the current study to conduct the estimation of annual CH_4 emissions from MSW due to the lack of historical data on waste composition and disposal practices. The default method is a mass balance approach; it can be applied as a standard tool for CH_4 emissions inventory from waste sector at whole regions or countries [6]. This method depends on estimating *DOC* content of waste, and using it to calculate amount of CH_4 that can be generated. This method assumes that all potential of CH_4 is released from waste in the year that the waste is disposed of, which overestimates emission estimation compared with the FOD method. The annual CH_4 emission (Gg) for each region or country can be calculated using (2) [6]:

$$Emission = \begin{pmatrix} MSW_T \times MSW_F \times MCF \times DOC \\ \times DOC_F \times F \times {}^{16}\!/_{12} - R \end{pmatrix} \times (1 - OX) \quad (2)$$

where MSW_T is the total MSW generated (Gg/y), MSW_F is the fraction of MSW disposed of at landfills which is 0.84 provided by Oman Environmental Services Holding Co. SAOC–be'ah [10]. The *MCF* is the CH_4 correction factor (fraction) which depends on the types of MSW landfill practices; the default values are ranging between 0.4 and 1.0 (Table I) [6].

TABLE I
Solid Waste Disposal Sites Classification and MCF

Type of site	CH_4 correction factor (MCF)
Managed	1.0
Unmanaged – deep (≥ 5m waste)	0.8
Unmanaged – shallow (< 5m waste)	0.4
Default value – uncategorized SWDSs	0.6

In according to Oman Environmental Services Holding Co. SAOC – be'ah the most of landfills in Sultanate of Oman are unmanaged shallow, therefore, a value of 0.4 was used. *DOC* is the degradable organic carbon (fraction), which depends on waste compositions. The computation of *DOC* fraction is essential for estimation CH_4 generation, and determine as shown in (3):

$$DOC = 0.4A + 0.17B + 0.15C + 0.3D \quad (3)$$

where A = paper, B = leaves + hay +straw, C = fruits + vegetables, and D = wood. According to [1], the waste composition in Sultanate of Oman provided an "A" value of 0.25, "B" value of 0.05, "C" value of 0.33, and "D" value of 0.016, which resulted with a value of 0.16414 of *DOC* content.

The DOC_F is dissimilated organic fraction, which is the

portion of *DOC* that is converted to LFG. Estimation of DOC_F is based on theoretical model varies with degree of temperature in the anaerobic zone of landfills (4):

$$DOC_F = 0.014T + 0.28 \quad (4)$$

where T is waste temperature (°C), with an assumption that 35° C is a constant temperature of the anaerobic zone at landfill; the DOC_F is 0.77. F in (2) is CH_4 fraction in LFG, the default value for CH_4 fraction in the IPCC 1996 guideline is 0.5 which was used in the current study. The R is the CH_4 recovered value (Gg/y) and OX is the cover soil oxidation factor (fraction). In the current study, the R value was set equal to zero where there is no gas recovery facility in the Sultanate of Oman. The default value of oxidation fraction is zero in the IPCC 1996 guideline [6], which was assumed throughout the calculation.

IV. Results and Discussion

A. Total Waste Generation 1971-2030

The annual per capita waste generation of Oman was estimated by entering the energy consumption data in [11] models prepared for developed and developing countries. The energy consumption data was provided by World Bank from 1971 to 2011. The annual waste generation resulted from [11] models and per capita waste generation data collected from The Report: Oman 2012 Oxford Business Group for the years 2004, 2009, and 2010, shown in Fig. 1.

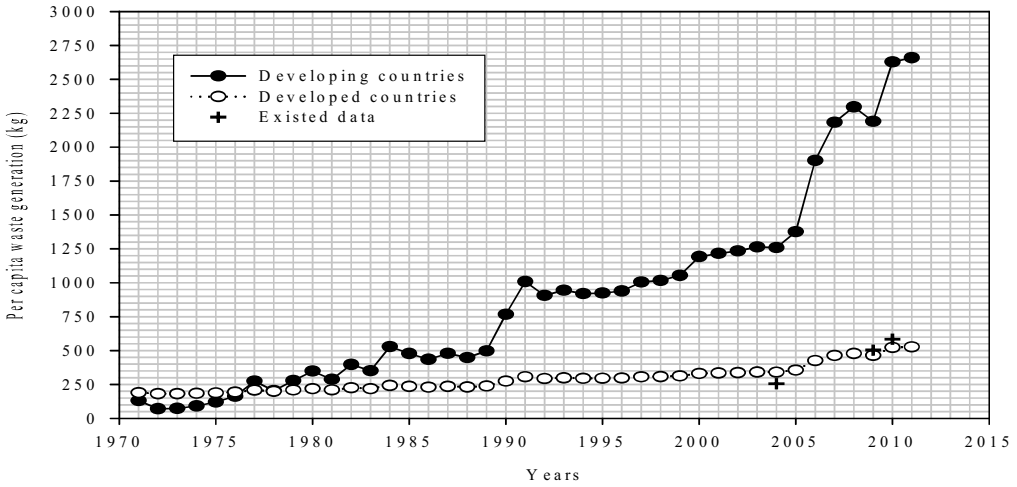

Fig. 1 Annual per capita waste generation

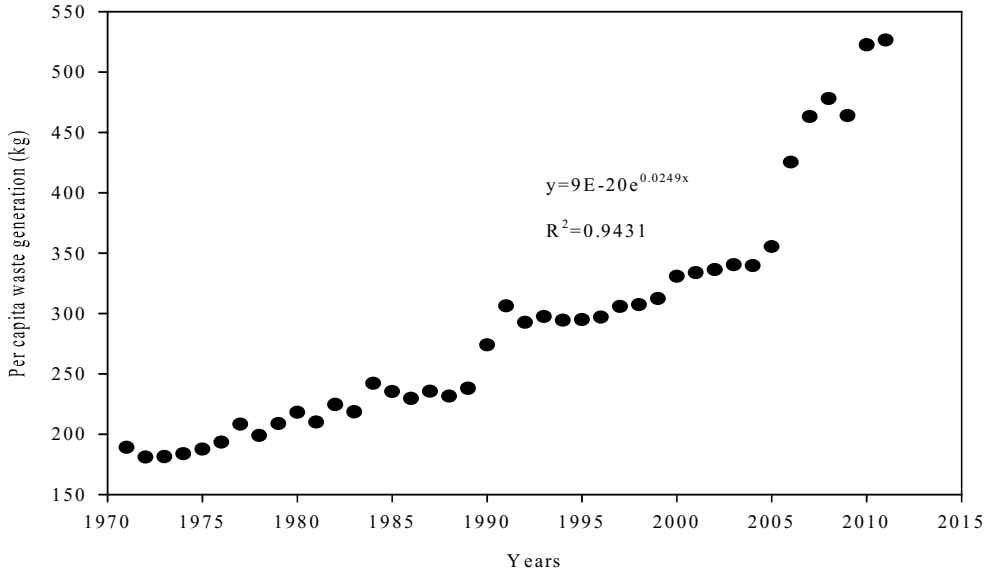

Fig. 2 Exponential regression model for prediction waste generation

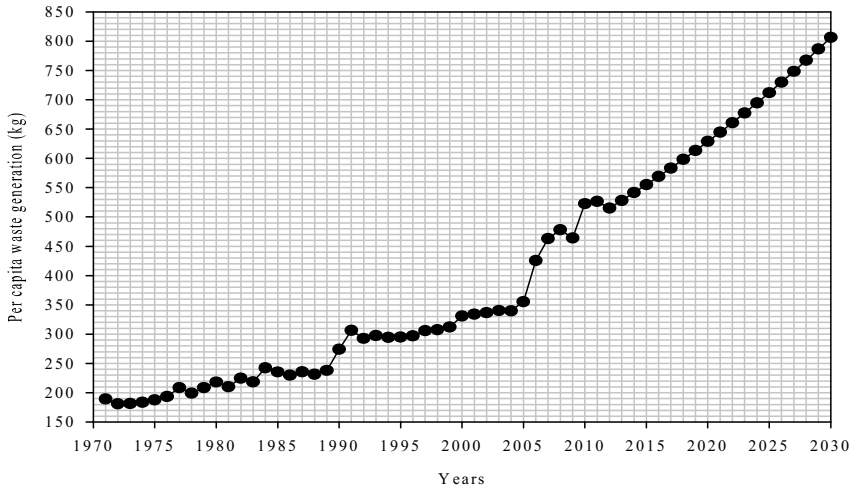

Fig. 3 Annual waste generations from 1971-2030

The results obtained from RMSE formula (1) shown that the model prepared for developed countries had RMSE equal 37.2 kg waste per capita, whereas the model prepared for developing countries had RMSE equal 944.9 kg waste per capita. This indicated that the model prepared for developed countries fitted the existed waste generation data with less RMSE value as compared to that prepared for developing countries. Therefore, the model prepared for developed countries was selected and used in this study to estimate annual waste generation in Oman from 1971 till 2011 depending on annual energy consumption available. Subsequently, exponential regression model was fitted the data on annual waste generation with correlation coefficient (R^2) value of 0.9431 (Fig. 2), and used for estimation future annual per capita waste generation till 2030 (Fig. 3).

Using the annual historic and projected population data and the annual per capita waste generation estimated, the total historic and projected waste generation for the time series 1971-2030 were estimated.

The results on waste generation per capita of Oman from 1971–2030 shown an increasing trend of the solid waste generation rate in Oman. This was due to the increase in the population of Oman over the years.

B. Total CH_4 Emissions

Number The annual CH_4 emissions from solid waste sector in the Sultanate of Oman is presented in Fig. 4.The results shown the increasing trend of CH_4 emissions with the increase in population and total MSW over the years. Methane emissions correlated positively with the population and total MSW generated, whereas when the population and total MSW are increased, the higher CH_4 emissions generated.

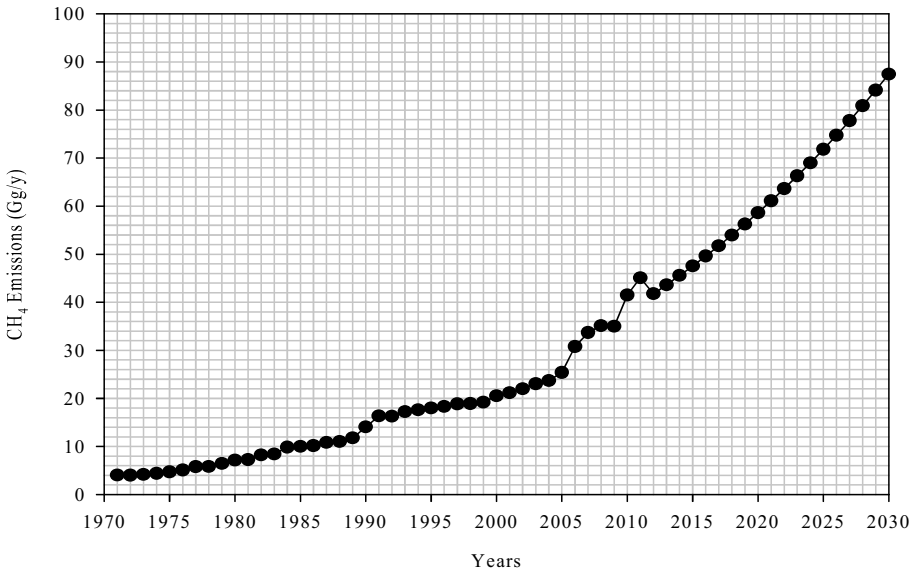

Fig. 4 CH_4 emissions from 1971 – 2030

The results have shown that the CH_4 emissions in the year 2011 were increased by approximately 90% in contrast to emissions in the year 1971, with emissions rate increased by about 1 Gg annually. The predicted CH_4 emissions in the year 2030 were increased by approximately 52% from the emissions in the year 2012, with emission rate increased by approximately 2.4 Gg annually. The highest CH_4 emissions rate from the years 2012 to 2030 in contrast to that from the years 1971 to 2011 might be because the high amount of waste generated due to several factors included population, income level, rapid development, rapid urbanization and increased migration patterns from rural to urban areas, and demographic and geographical factors.

In comparison with other Asian countries, Oman has shown relatively higher level of per capita CH4 emissions resulted from solid waste. It was estimated that approximately 319 Gg of CH_4 emissions generated from MSW in Malaysia for the year 2009 using the IPCC 1996 FOD model [12], which is consistent with the value of CH_4 emissions estimated in this study with considering the population in each country. In Thailand, MSW emitted approximately 121 Gg of CH_4 in 2005 [13], this was estimated using the IPCC 1996 FOD model. In 2006, the total CH_4 emission in Thailand was re-estimated by [14] using the IPCC 2006 FOD model, where they found about 90 Gg of CH_4 generated from MSW. On average 382 Gg of CH_4 emitted from MSW generated in India between the years 1980 and 1999 using the default method [7]. Using the same method, [4] found that 2,621 Gg of CH_4 emitted from China in the year 2004. The huge differences among CH_4 emissions from those countries might be due to the different in the amount of waste generated, waste composition and characteristics, waste age, population, disposal practices, and environmental conditions.

V. Conclusion

In this study, the MSW and its CH_4 emissions inventory were estimated in Oman over the years 1971–2030. It was found that total MSW of Oman in the year 1971 was 141.6 Gg/year which enormously increased to 1464.4 Gg/year by the year 2010 and is expected to increase by 3089.1 Gg/year in the year 2030. This increased in the amount of waste emphases on that management of solid waste should be tackled all the environmental, operational, and social aspects to minimize the waste impacts on both human health and environment. This includes the management of resources in an environmentally sound and economically effective manner.

The total amount of CH4 emitted is obtained by using the IPCC Default method. From the results obtained it can be seen that total 4.01 Gg/year CH_4 was emitted in the year 1971 which enormously increased to 41.46 Gg/year in the year 2010, and it is expected to increase by 87.46 Gg/year by the year 2030. Therefore it can be concluded that an increasing trend in CH_4 emissions in Oman with respect to the population and total MSW. The CH_4 emissions of Oman are also compared with other Asian countries such as Malaysia, Thailand, India, and China, the reason behind vast difference in the CH_4 emissions is due to the large difference in population.

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