applied sciences

MDPI

Article

Greenhouse Gas Emissions from Solid Waste Management in Saudi Arabia—Analysis of Growth Dynamics and Mitigation Opportunities

Muhammad Muhitur Rahman [1,*], Syed Masiur Rahman [2], Mohammad Shahedur Rahman [3], Md Arif Hasan [4], Syed Abu Shoaib [1] and Sayeed Rushd [5]

1 Department of Civil and Environmental Engineering, College of Engineering, King Faisal University, Al-Ahsa 31982, Saudi Arabia; sabushoaib@kfu.edu.sa
2 Center for Water and Environment, Research Institute, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia; smrahman@kfupm.edu.sa
3 Civil Engineering Department, College of Engineering, Al-Imam Mohammad Ibn Saud Islamic University, Riyadh 13318, Saudi Arabia; msrahman@imamu.edu.sa
4 School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington 6012, New Zealand; md.arif.buet@gmail.com
5 Department of Chemical Engineering, College of Engineering, King Faisal University, Al-Ahsa 31982, Saudi Arabia; mrushd@kfu.edu.sa
* Correspondence: mrahman@kfu.edu.sa

Abstract: The continuous growth in population, urbanization, and industrial development has been increasing the generation of solid waste (SW) in the Kingdom of Saudi Arabia. Consequently, the associated greenhouse gas (GHG) emission is also following an increasing trend. The collection and use of greenhouse gases emitted from solid waste management practices are still limited. A causality analysis examined the driving factors of the emissions from solid waste management. The methane (CH_4) emissions from municipal solid waste (MSW) increased with an increase in gross domestic product (GDP) per capita and urban population, and an increase in foreign direct investment (FDI) inflows and literacy rate was likely to reduce CH_4 emissions from municipal solid waste and vice versa. The CH_4 emission generated from industrial solid wastes was found to be positively related to GDP per capita, urban population, and FDI inflows. However, a decrease in the unemployment rate was likely to increase CH_4 emissions from industrial solid wastes. The future greenhouse gas emissions were projected under different possible socio-economic conditions. The scenario analysis based on different variations of population and GDP growth revealed that methane emission from total waste would increase at an average annual rate of 5.13% between 2020 and 2050, and is projected to reach about 4000 Gg by the end of the year 2050. Although the Kingdom has been taking some initiatives towards climate change mitigation, it has significant opportunities to adopt some of the best practices in solid waste management including reduction, recycling, composting and waste-to-energy, and carbon capture and utilization. This study also put emphasis on developing appropriate policy approaches for climate change mitigation based on the circular economy which is gaining momentum in the Kingdom.

Keywords: methane emission; municipal solid waste; industrial solid waste; IPCC; causality analysis; VECM models; VISION 2030

check for updates

Citation: Rahman, M.M.; Rahman, S.M.; Rahman, M.S.; Hasan, M.A.; Shoaib, S.A.; Rushd, S. Greenhouse Gas Emissions from Solid Waste Management in Saudi Arabia—Analysis of Growth Dynamics and Mitigation Opportunities. *Appl. Sci.* **2021**, *11*, 1737. https://doi.org/10.3390/app11041737

Academic Editor: Sung-Deuk Choi
Received: 18 November 2020
Accepted: 8 February 2021
Published: 16 February 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The developed and developing countries have been exerting efforts to adopt appropriate climate change mitigation initiatives depending on many factors including international agreement, national climate policy and priority, socio-economic conditions, natural resources, technological advancement level, and human resources. Developing countries

have been facing the challenges to select suitable sectors and adopting appropriate mitigation measures. This study selected the solid waste management sector to trace the dynamics and the associated greenhouse gas (GHG) emissions. Greenhouse gases have environmental and health effects. They trap heat which ultimately causes climate change, and they also create smog and air pollution which causes respiratory disease. The increased number of extreme weather events and famine caused by food supply disruptions and increased wildfires are other effects of climate change caused by greenhouse gases. The global GHG emissions from solid waste management have been following an increasing trend [1].

Solid waste (SW) generation rates and composition vary across different regions of the world as it is a function of demographic and socio-economic factors such as local economy, industrial development, population and economic growth, industrialization and urbanization, waste management system, and lifestyle applicable to each country [2–4]. The most frequently used parameter for determining total waste generation and forecasting rate is population [5,6]. Per capita solid waste generation rates are not influenced by demographic parameters, rather by other factors [7].

Worldwide, post-consumer waste was estimated to produce about 1300 Mt CO_2 eq in 2005, most of which was attributed to landfill and waste compost [8,9]. Methane and carbon dioxide (CO_2) are the most dominant types of GHG from the disposal site. Solid waste that is processed in these landfills and waste compost systems are a critical element in estimating GHG emission. Due to economic growth, the standard of living in Saudi Arabia has been, elevated which has resulted in higher SW generation [10,11]. According to Hoornweg and Bhada–Tata [12], approximately 1.3 billion tons of municipal solid waste (MSW) were produced in 2012 and with the current rate of development, it is projected to be 2.2 billion tons of MSW in the year 2025. At present, the Middle East and North African region has a MSW production rate of 1.1 Kg/capita/day which is estimated to be 1.43 Kg/capita/day in 2025. Prominent cities of the Arab world such as Kuwait and Abu Dhabi produce about 1.5 kg SW per capita per day which results in nearly 250,000 tons SW per day for the Arab region [13].

Due to urbanization and growth in wealth, SW generated per capita is growing [14]. Income and demographic indices are the most frequently reported factors in MSW research [15,16]. Gross domestic product (GDP) and population density are reported to have a strong positive correlation with MSW production in China and EU [17]. The environmental Kuznets curve (EKC) postulated that there is an inverted U-shaped relationship between per capita income and environmental degradations [18]. Thus, according to this hypothesis with consistent economic growth, ultimately MSW production will be reduced [19]. A recent report confirmed that the EKC hypothesis holds for Switzerland and bidirectional causality exists between MSW generation and GDP per capita [20]. A statistically significant linear correlation (Pearson's correlation coefficient r = 0.607 with $p < 0.001$) had been observed between the income per capita and the annual municipal solid waste generation from research conducted on 39 municipalities in Brazil. A similar relationship was reported for Europe by others [21].

Factors such as consumption patterns and financial expenditure have an impact on MSW generation. Researchers reported from China that family size, income, and education level also have an impact on SW generation rate per household [22]. Studies from Vietnam reported that higher-income families produce less SW and organic fraction per household but more paper and plastic. They also reported that as the education level and family size increase, the household SW generation rate increases [23]. Family size has been shown to have positive correlation with the SW generation rate in India [15]. However, researchers observed that families with median income generated a maximum amount of SW. A study from the agro-industrial region of Podlasie province in northeastern part of Poland revealed that gender, age, and employment rate could influence municipal waste generation rate. The study showed that women produce more waste than men, and the largest contributor is the working-age group from 14 to 64 years. The more employed women in this group,

the less the waste generation rate can be expected [24]. In another recent study, the artificial neural network (ANN) was used to analyze demographic and socio-economic data from 220 municipalities in Ontario, Canada. The researchers reported that populations with 45+ years of age have a negative correlation with MSW; thus, the older population creates less waste. However, income and employment have a positive correlation [25].

Emission from waste is heavily influenced by behaviors of the economic and consumers of the society, and they are distinct from other emissions (i.e., SO_2, PM) which are production- and activity-based. Lee et al. [19] used the Granger causality test to identify the causal relationship among waste generation, waste emissions, recovery waste generation, and GDP. They reported no causality between GDP and waste generation, but total waste and recycling generation significantly cause positive and negative greenhouse gas emissions from the waste sector, respectively. On the other hand, Song et al. [26] reported evidence supporting an inverted U-shaped relationship between waste emission and GDP using 20 years of (1985–2005) data from 29 Chinese provinces. Ari and Şentürk [27] investigated the relationship between waste emission (i.e., CH_4) and GDP per capita for G7 countries. They reported no evidence for the traditional environmental Kuznets curve (EKC) hypothesis and observed an inverted N-shaped curve between CH_4 emission and GDP per capita. The study recommends that increasing GDP per capita should be aligned with strong policies for sustainable consumption and production and increasing the efficiency of resources will reduce waste emission.

The municipal solid waste management operation usually consists of several sequential activities after generation, which include collection, transportation, and treatment [28]. All these activities from generation to treatment are significant sources of GHG emission [29]). Biodegradable organics, which occupies a significant portion of MSW, could increase GHG emissions. Globally, the waste management sector generates approximately 1.3 Gt CO_2 e every year. This sector is responsible for about 2.8% of total emissions of GHG [3].

The organic degradable segment of MSW usually derives from consumed vegetable and fruit [30]. All over the world landfills are the most common practice for solid MSW disposal [31]. Organic components in the lower layers of open dumps and landfills are decomposed by the anaerobic process, generating landfill gas (LFG) containing about 50–60% methane [32]. The rate of methane production depends on waste characteristics, moisture content, quantity, age, and oxygen availability [33]. Methane has a shorter atmospheric life span and in terms of global warming potentials (GWP) is 21 times stronger than CO_2. Landfills are one of the largest anthropogenic sources of methane emission [34]. According to the United States Environmental Protection Agency (USEPA) methane emissions from landfill in Asia, Latin America, and Africa, is equivalent to 37 million metric tons of CO_2, which is equivalent to emissions from more than 102 million automobiles [32]. It is reported that less than 10% of the methane potential is being captured and utilized [35]. Landfill gas at a high concentration also causes the risk of explosion [36] and odor problems [37]. Due to the heterogeneous nature of MSW, unreliable data on production rate, diversity in collection and treatment, and the complex biological processes involved in an accurate estimation of GHG, methane emission is quite complicated.

Saudi Arabia is the largest country in the Middle East, which occupies about four-fifths of the Arab Peninsula, with a land area of around 2,149,690 square kilometers [38]. According to the United Nations [39], the total population of Saudi Arabia in 2019 was 34 million, which makes it the most populous country in the Middle East. Due to significant annual growth rate in population (2.3% between 2010 and 2015), total SW generation is expected to increase proportionally. Financial indices such as GDP or Gross National Product (GNP) and per capita income not only have a direct correlation with per capita SW generation rate, but also with the composition of SW. It is reposted that the per capita income of the kingdom increased at 5.26% for the period 1996–2013. This growth was also accompanied by improvement of other human indicators such as education, life expectance, infant mortality rate, etc. The effect of all these factors is not always synergistic

on SW generation. For example, studies showed that people with higher education levels generated less waste [40]. During the past three decades, the education sector in the kingdom made significant improvements and the literacy rate was reported to be 94% in 2013. Thus, the effects of the increase in per capita income and education level will counteract each on per capita SW generation.

The above literature review suggests that the main driving factors of the type and the quantity of solid waste generation include urbanization, GDP, employment rate, literacy, gender, lifestyle, household size, population density, old population, economic growth, industrial growth, etc. Emissions from solid waste management systems mainly depend on solid waste management practices, climatic conditions, share of recycling, and emission management system. Many of the driving factors have been following an increasing trend in the Kingdom of Saudi Arabia. Therefore, there is a need to analyze the driving factors and their impact on the greenhouse gas emissions from solid waste management practices. In this study, we adopted a causality-based analysis to trace the impact of selected driving factors on emissions. To support the policy-making process, this study generated a few possible emission scenarios along with suitable climate change mitigation opportunities.

2. Materials and Methods

The steps involved in the growth dynamics analysis and projection of methane emission from the waste sector are shown in Figure 1. At first, available data on different parameters related to waste generation were collected, and causality analysis was performed to examine the best-correlated parameters to methane emission due to municipal and industrial waste disposal. Then a methane emission model proposed by the Intergovernmental Panel on Climate Change, IPCC [3] was used to predict emissions from the year 2020 to 2050. Later, different scenarios in terms of waste diversion were modeled and mitigation measures were proposed. For waste diversion scenarios, the impact of the reduction of municipal as well as industrial waste disposal by 0%, 25%, 50%, and 75% on methane emission was investigated.

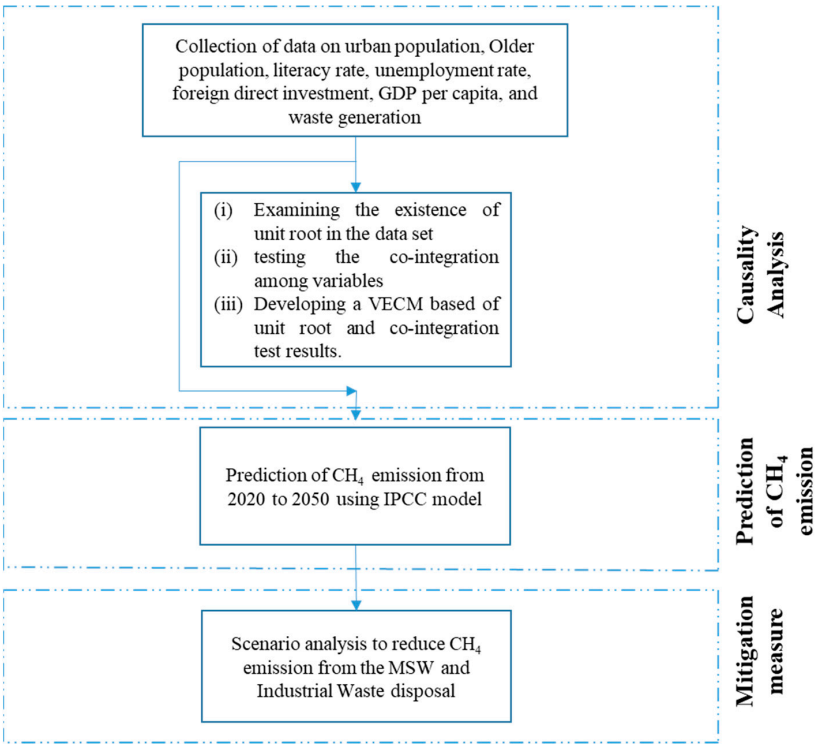


Figure 1. Steps involved for causality analysis and prediction modeling.

2.1. Causality Analysis

This study performed a causality analysis using the EViews statistical package to understand the key drivers of the municipality and industrial solid waste emissions in Saudi Arabia. A number of drivers were examined including GDP per capita (GDPPC), urban population (UPOP), foreign direct investment inflows (FDI), literacy rate (LR), older population (OP), and unemployment rate (UR). Two separate vector error correction models (VECM) were developed for municipal solid waste emissions and industrial solid waste emissions so that the drivers of each type of emissions could be explored comprehensively. Through developing the VECM, both short- and long-run causality analyses between solid waste emissions from their drivers were performed. The details of the data used in these models are provided in Table 1, followed by model specifications and major steps of VECM development.

Table 1. Data used in causality analysis.

Data (Symbol)	Description	Period	Unit	Source
CH_4 emissions from municipal solid waste (MSW)	This includes CH_4 emissions generated from municipal solid wastes in Saudi Arabia	1970–2019	Gigagram (Gg)	IPCC [3]
CH_4 emissions from industrial solid waste (ISW)	This includes CH_4 emissions generated from industrial solid wastes in Saudi Arabia	1970–2019	Gigagram (Gg)	IPCC [3]
Older population (OP)	This presents the total number of population at the age of 60 and over	1970–2019	Years	World Bank [38]
Literacy rate (LR)	This shows the percentage of people who can read and write in Saudi Arabia	1970–2019	%	World Bank [38]
Unemployment rate (UR)	This shows the share of Saudi Arabia's labor force who are unemployed but seeking employment opportunities	1970–2019	%	World Bank [38]
Foreign direct investment inflows (FDI)	This presents the monetary value of inward direct investments made by non-resident investors in Saudi Arabia	1970–2019	Current USD	World Bank [38]
Urban population (UPOP)	The total number of population living in urban areas	1970–2019	Person	United Nations Statistics Division [39]
GDP per capita (GDPPC)	The monetary value of all domestic products produced in a year in Saudi Arabia, divided by the country's population	1970–2019	US dollar (USD)	World Bank [38]

2.1.1. Model Specifications

As said earlier, this study developed two separate models for the two categories of solid waste emissions: CH_4 emissions from municipal solid waste (MSW) and CH_4 emissions from industrial waste (ISW). For each category of solid waste emissions, a range of independent or explanatory variables were identified. Model 1 considered CH_4 emissions from municipal solid waste (MSW) as the dependent variable and GDP per capita (GDPPC), urban population (UPOP), FDI inflows (FDI), older population number (OP), and literacy rate (LR) as independent or explanatory variables. The independent or explanatory variables for CH_4 emissions from industrial waste (ISW) include GDPPC, UPOP, FDI, and unemployment rate, and their relationships are presented in Model 2.

Model 1 and model 2 are specified in Equations (1) and (2), respectively.

$$(MSW)_t = \alpha_1 + \beta_1\, GDPPC_t + \beta_2\, UPOP_t + \beta_3\, FDI_t + \beta_4\, OP_t + \beta_5\, LR_t + \varepsilon_{1t} \quad (1)$$

$$(ISW)_t = \alpha_2 + \beta_6\, GDPPC_t + \beta_7\, UPOP_t + \beta_8\, FDI_t + \beta_9\, UR_t + \varepsilon_{2t} \quad (2)$$

where α_1 and α_2: The intercepts; t: The year; β_1 to β_9: Coefficients for independent or explanatory variables; and ε_1 and ε_2: Constant error terms.

The examination of stationarity and non-stationarity of time series data was the initial step for developing a VECM, and this required a logarithmic form of the proposed models (Equations (1) and (2)). Equations (3) and (4) represent the logarithmic form of Equations (1) and (2), respectively.

$$\text{Ln (MSW)}_t = \ln(\alpha_1) + \beta_1 \ln(\text{GDPPC}_t) + \beta_2 \ln(\text{UPOP}_t) + \beta_3 \ln(\text{FDI}_t) + \beta_4 \ln(\text{OP}_t) + \beta_5 \ln(\text{LR}_t) + \ln \varepsilon_{1t} \quad (3)$$

$$\text{Ln (ISW)}_t = \ln(\alpha_2) + \beta_6 \ln(\text{GDPPC}_t) + \beta_7 \ln(\text{UPOP}_t) + \beta_8 \ln(\text{FDI}_t) + \beta_9 \ln(\text{UR}_t) + \ln \varepsilon_{2t} \quad (4)$$

2.1.2. Developing VECM Models

The major steps for understanding causal relationships among the dependent and independent variables include (i) examining the existence of unit roots in the data set, (ii) testing the co-integration among variables, and (iii) developing a VECM based on unit root and co-integration test results.

Both the augmented Dickey–Fuller (ADF) test and Phillips–Perron (PP) test were performed to examine the existence of unit roots in a variable. The presence of unit roots indicates the non-stationarity of a time series variable [41] and one of the preconditions for using a time series variable in a vector error correction model (VECM) is that the variable needs to be non-stationary at the level and stationary at the first difference [42]. The ADF test was deployed in this study because it is one of the most widely used unit root tests [43]. On the other hand, the PP test is adopted along with the ADF test because the strength of an ADF test to reject a unit root is often limited [44]. Moreover, Hasan et al. [41] confirmed that the combination of both the tests is likely to provide robust results.

Based on the results of the unit root, this study adopted the Johansen's test of co-integration to understand if any of the two variables (both dependent and independent variables) were co-integrated. The precondition for developing a VECM model was that at least two variables had to be co-integrated among each other. To investigate the existence of co-integration among different variables, trace statistics (TS) and maximum eigenvalue statistics (MES) were considered. It was assumed that the use of two different statistics would provide reliable results. Finally, based on the unit test and co-integration test results, this study developed the VECM for each emission type and performs the Granger causality test to understand the short- and long-run causal relationship between solid waste emissions and their drivers.

2.2. Methane Emission Calculation

The IPCC [3] method for estimating methane emissions from solid waste disposal sites was based on the first order decay model, which assumes a slow decay of degradable organic carbon in solid waste to methane and carbon dioxide. The model was approximated by the first-order kinetics. The model produced acceptable results for wastes having a historical time period of 3 to 5 half-lives in the landfill. Therefore, a waste disposal data of greater than 50 years produce an acceptable result. The methane emissions were calculated by Equation (1) [3]:

$$CH_4 \; Emission \; in \; Gg = \left[\sum_x CH_4 \; Generated_{x,\,T} - R_T \right] \times (1 - OX_T) \quad (5)$$

where T = inventory year; x = waste category; R_T = recovered CH_4 in year T (Gg); OX_T = oxidation factor in year T. The oxidation factor represents the amount of methane that is oxidized in the soil or other material covering the waste. The methane generation in the landfills was calculated using Equations (2)–(5):

$$DDOC_m = W \times DOC \times DOC_f \times MCF \quad (6)$$

where $DDOC_m$ is the mass of decomposable DOC deposited, DOC is the amount of degradable organic carbon deposited in the year of interest as a fraction (Gg C/Gg waste), DOC_f is the fraction of DOC that could be decomposed, and MCF is the methane correction factor (as a fraction) for aerobic decomposition in the year the waste was deposited.

$$DDOCma_T = DDOCmd_T + \left(DDOCma_{T-1} \times e^{-k}\right) \quad (7)$$

where $DDOCma_T$ and $DDOCma_{T-1}$ are the $DDOC_m$ accumulated in the landfill at the end of year T and year $T-1$ (Gg), respectively; $DDOCmd_T$ is the $DDOC_m$ deposited in the landfill in year T (Gg), k is the reaction constant ($k = \ln(2)/t_{1/2}$), where $t_{1/2}$ is the half-life time (year).

$$DDOC_m decomp_T = DDOCma_{T-1} \times \left(1 - e^{-k}\right) \quad (8)$$

where $DDOC_m decomp_T$ is the mass of $DDOC$ decomposed in year T (Gg);

$$CH_4\ Generated_T = DDOC_m decomp_T \times F \times \frac{16}{12} \quad (9)$$

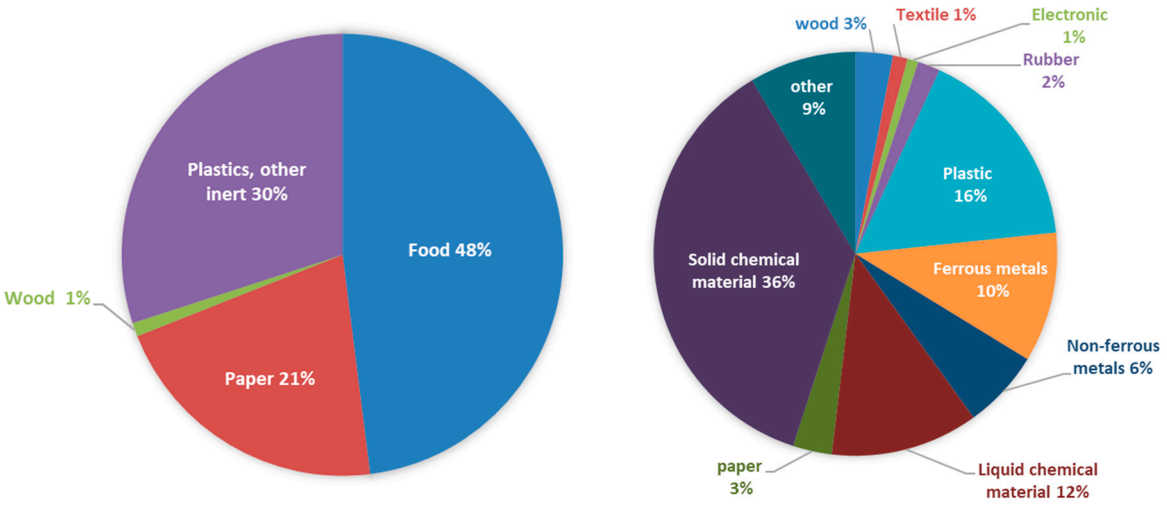
where F = fraction of methane by volume in generated land-filled gas, and 16/12 is the ratio of molecular weight between methane and carbon.

2.3. Waste Collection Practices in Saudi Arabia

The general practice of the collection of MSW in Saudi Arabia is based on a communal system, where open collection containers (5 m^3) are kept in public places and the nearby residents and commercial users dump their comingled wastes (mixed solid waste) in the container. Generally, old shopping bags or trash plastic bags are used for bagging the waste and dumping into the container [45]. In some places, curbside collections are observed, where small barrel-type containers (0.25 m^3) are used to collect the residents' disposed waste. Compaction or semi-compaction waste vehicles are used for curbside collection of waste, assisted by the manual emptying of waste containers to the compaction vehicles. The local municipality employs contractors to collect the waste, which is hauled either to the transfer station or directly to the landfill site. Most of the landfilled sites have no facilities for the collection of landfill gas, with some exceptions of Madinah and Jeddah (new and old) landfills [46].

For the management of non-hazardous industrial wastes in Saudi Arabia, MODON (Saudi Authority for Industrial Cities and Technology Zones) and Royal Commission for Jubail and Yanbu (RCJY) are the responsible organizations. MODON offers non-hazardous waste collection services from factories through its own contractor, who dumps the wastes in the landfill. On the other hand, RCJY encourages the industries under its jurisdiction to recycle or reuse industrial waste.

The composition of municipal solid waste in Saudi Arabia varies based on community to community, rural/urban, and agricultural/non-agricultural areas. In urban areas, food waste is the largest fraction of MSW, which is about 50.6% [47], followed by plastic (5–17%), textiles (6.4%), glass (4.6%), and metals (8.1%) [48]. In areas where agricultural activities including date palm farming are prominent, a considerable quantity of green waste (about 6.8%) is observed [45]. The composition of municipal solid waste used in this paper for estimation of CH_4 generation from landfill is shown in Figure 2. On the other hand, industrial waste is mainly composed of solid and liquid chemical waste, plastic, ferrous and non-ferrous metal, wood, paper, rubber, textiles, and electronic waste, as shown in Figure 2.



(**a**) (**b**)

Data (Symbol)	Description	Period	Unit	Source
CH_4 emissions from municipal solid waste (MSW)	This includes CH_4 emissions generated from municipal solid wastes in Saudi Arabia	1970–2019	Gigagram (Gg)	IPCC [3]
CH_4 emissions from industrial solid waste (ISW)	This includes CH_4 emissions generated from industrial solid wastes in Saudi Arabia	1970–2019	Gigagram (Gg)	IPCC [3]
Older population (OP)	This presents the total number of population at the age of 60 and over	1970–2019	Years	World Bank [38]
Literacy rate (LR)	This shows the percentage of people who can read and write in Saudi Arabia	1970–2019	%	World Bank [38]
Unemployment rate (UR)	This shows the share of Saudi Arabia's labor force who are unemployed but seeking employment opportunities	1970–2019	%	World Bank [38]
Foreign direct investment inflows (FDI)	This presents the monetary value of inward direct investments made by non-resident investors in Saudi Arabia	1970–2019	Current USD	World Bank [38]
Urban population (UPOP)	The total number of population living in urban areas	1970–2019	Person	United Nations Statistics Division [39]
GDP per capita (GDPPC)	The monetary value of all domestic products produced in a year in Saudi Arabia, divided by the country's population	1970–2019	US dollar (USD)	World Bank [38]

Figure 2. Composition of (**a**) municipal solid waste (MSW) [3] and (**b**) industrial waste [49] in Saudi Arabia.

2.4. Estimation of the Urban Population, GDP, and Amount of Solid Waste

Data on the population of Saudi Arabia were extracted from the United Nations [39], which estimated the population based on trends in the demographic components of population change including fertility, mortality, and migration. For projecting the future levels of fertility and mortality, the United Nations [39] used a probabilistic method taking into account the historical variability of uncertainty. In this paper, three projections, namely

low, medium, and high variant projections were used, which is shown in Figure 3. In the high variant assumptions, 0.5 births above the total fertility of the medium variant were used, and in the low variant assumption, 0.5 births below the total fertility of the medium variant were used [39]. It should be noted in this regard that as a study area, the entire Saudi Arabia is considered for its urban population and generation of MSW. However, to examine the impact of urbanization on the CH_4 emission (Section 3.2.1), some major cities were considered.

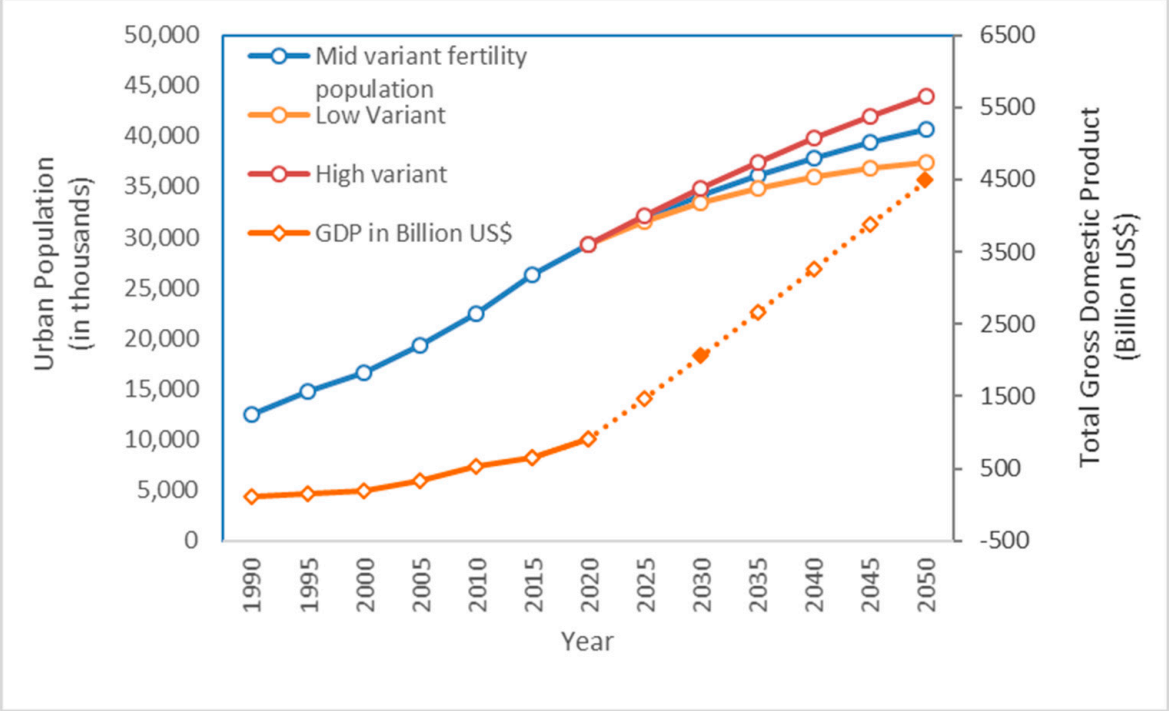


Figure 3. Population and gross domestic product (GDP) projection of Saudi Arabia [50,51].

The gross domestic product of Saudi Arabia from 1970–2019 was collected from World Bank [38]. The future GDP of Saudi Arabia from 2020–2050 was estimated based on the GDP predicted at market exchange rate by price water Cooper [50], considering the growth in the labor force of working age, increase in human capital, growth in the physical capital stock, and the productivity. The GDP was used in the IPCC model to calculate the CH_4 generation from industrial waste. According to GAS [49], about 20.25 million tons of industrial waste was generated in 2017; the value was used to estimate the yearly industrial waste generation rate per GDP as 0.0294 Gg/Million $GDP/year.

The per capita MSW generation in Saudi Arabia (Figure 4) between 2010 and 2017 ranged between 1.15 and 2.04 kg/capita/day [52], which is based on the total population of the country. The waste generation rate decreased in 2018 to 1.72 kg/capita/day, which is due to the encouragement of business owners by the government to recycle more and dump less [52]. However, due to the lack of published MSW generation data except 2010–2018, for the projection of total urban MSW generation, the value proposed by the IPCC [3] was used. The average MSW generation rate for Saudi Arabia proposed by IPCC [3] is 470 kg/capita/year (1.29 kg/capita/day). The total amount of MSW (Equation (6)) was calculated based on the estimated population (Figure 3) and the solid waste generation rate:

$$Total\ amount\ of\ MSW_T = Per\ capita\ MSW_T \times Population\ projection \quad (10)$$

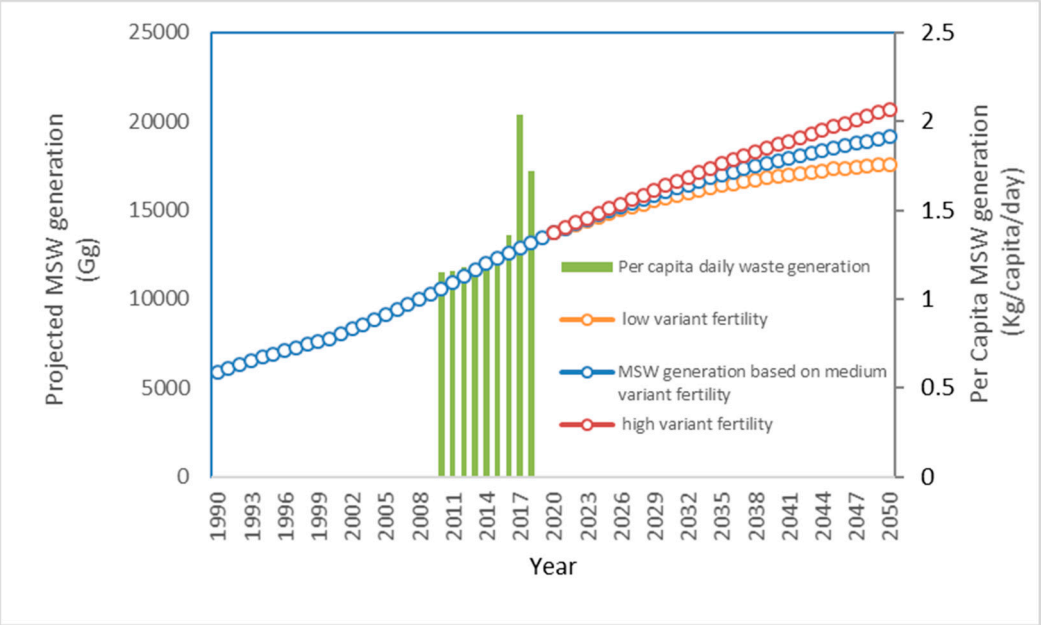


Figure 4. Per capita [52], historical, and projected (2020–2050) total urban MSW generation in Saudi Arabia.

Figure 4 shows the projected amount of total urban MSW for three population scenarios from 1990 to 2050. The yearly generated amount of MSW was used in the IPCC model for the calculation of CH_4 generation. Tables 2 and 3 summarize the parameters used along with their value, and input parameters for waste composition in the IPCC model.

Table 2. Assumptions and parameters used in calculating CH_4 emission in the IPCC [3] model.

Parameters	Assumptions/Value/Time Series	Data Source
Starting year	1970	
Urban population (in millions)	1970–2050	United Nations [39]
Total gross domestic product (GDP) (at current USD)	1970–2019	World Bank [38]
	2020–2050	Price Water Cooper [50]
Period of methane calculation	1970–2050	
Per capita waste generation	470 kg/capita/year	[3,53]
% MSW disposed to landfill	96%	[3]
Fraction of methane in developed gas	0.5	
C to CH_4 conversion factor	16/12	
Oxidation factor	0 (for managed landfill)	
Methane correction factor	0.6	
Delay time	6 months	

Table 3. Input parameters for waste composition in Saudi Arabia used in the IPCC [3] model.

Waste Composition	% Disposed to Landfill	Degradable Organic Carbon (DOC)	Fraction of DOC Decomposed (DOC_f)	Rate of Reaction Constant (k)	Half-Life Time ($t_{1/2}$)
Food	48%	0.15	0.7	0.085	8.2
Paper	21%	0.4	0.5	0.045	15.4
Wood	1%	0.43	0.1	0.025	27.7
Plastics, other inert	30%	0			
Industrial waste	100%	0.150	0.7	0.065	10.7

3. Results and Discussion

3.1. Causality Analysis

3.1.1. Unit Root Test

Table 4 presents the results of unit root tests for each of the variables. It is evident from Table 4 that except for older population (OP) data, all the other variables were non-stationary at level but stationary at first difference. Therefore, the older population data will not be used in the VECM development as they did not meet the criteria. Other independent or explanatory variables are suitable for developing VECM models.

Table 4. Unit root test of dependent and independent variables.

At Level	ADF Test (*t*-Statistics)		PP Test (*t*-Statistics)	
	Intercept (I)	Intercept and Trend (I&T)	Intercept (I)	Intercept and Trend (I&T)
MSW	7.88 (0)	−3.12 (0)	5.35 (4)	−2.95 (2)
ISW	0.96 (10)	−2.22 (10)	2.24 (4)	−0.54 (4)
GDPPC	−0.96 (0)	−1.53 (0)	−1.09 (1)	−1.80 (2)
UPOP	0.02 (1)	−2.69 (1)	2.53 (5)	−1.56 (5)
FDI	−2.60 (1)	−2.56 (1)	−2.00 (2)	−1.85 (2)
OP	2.02 (1)	0.42 (1)	6.66 (5)	3.23 (4)
LR	−1.97 (0)	−1.39 (0)	−1.93 (1)	−1.39 (0)
UR	−2.3 (1)	−2.62 (1)	−2.00 (2)	−2.13 (3)
At First Difference				
MSW	−2.98 ** (0)	−5.44 ***(0)	−2.66 * (2)	−5.50 *** (3)
ISW	−1.55 (9)	−2.84 * (9)	−1.94 (3)	−1.69 (3)
GDPPC	−5.20 *** (0)	−5.15 *** (0)	−5.18 *** (2)	−5.13 *** (2)
UPOP	−2.04 (0)	−1.73 (0)	−2.96 * (3)	−1.99 (3)
FDI	−4.75 *** (0)	−4.72 *** (0)	−4.76 *** (2)	−4.73 *** (2)
OP	−0.52 (0)	−1.90 (0)	−0.51 (1)	−1.93 (1)
LR	−5.99 *** (0)	−6.37 *** (0)	−5.99 *** (1)	−6.36 *** (1)
UR	−4.87 *** (0)	−4.93 *** (0)	−4.87 *** (1)	−4.94 *** (1)

Note: Lag lengths are chosen based on the Schwarz Information Criterion (SIC) and presented within parenthesis. ***, **, and * illustrate the level of significance at 0.01, 0.05, and 0.1 level, respectively.

3.1.2. Johansen's Test of Co-Integration

The presence of at least one co-integrating equation is one of the pre-conditions for developing a VECM model. This implies that at least two of the time series variables used in this study needed to be integrated among each other [42]. The results of Johansen's test of co-integration for model 1 and model 2 are presented in Tables 5 and 6, respectively. Results show the presence of at least one co-integrating equation in the model at 0.05 level. This justifies the development of a VECM for this study instead of a vector autoregression (VAR) model.

Table 5. Results of Johansen's test of co-integration for model 1.

No. of Co-Integrating Equation (CE)	Hypothesis	Trace	Maximum Eigenvalue
$r = 0$	No CE	109.00 ***	56.88 ***
$r = 1$	At most 1 CE	52.12 **	22.08 **
$r = 2$	At most 2 CE	30.04	18.85
$r = 3$	At most 3 CE	11.19	11.04
$r = 4$	At most 4 CE	0.15	0.15

Note: ** and *** illustrate the level of significance at 0.05, and 0.01 levels, respectively.

Table 6. Results of Johansen's test of co-integration for model 2.

No. of Co-Integrating Equation (CE)	Hypothesis	Trace	Maximum Eigenvalue
$r = 0$	No CE	86.47 ***	32.69 *
$r = 1$	At most 1 CE	53.77 **	27.76
$r = 2$	At most 2 CE	26.01	15.91
$r = 3$	At most 3 CE	10.10	9.11
$r = 4$	At most 4 CE	0.98	0.98

Note: *, **, and *** illustrate the level of significance at 0.1, 0.05, and 0.01 levels, respectively.

Tables 7 and 8 present the co-integrating coefficients of various independent or explanatory variables for model 1 and model 2, respectively. The sign of a coefficient shows the relationship between an independent variable and the corresponding dependent variable. Results presented in Table 7 indicate that CH_4 emissions generated from municipal solid wastes in Saudi Arabia were positively correlated with GDP per capita and urban population. This implies that emissions from municipal solid waste increase with an increase in GDP per capita and urban population. The relationship running from FDI inflows and literacy rate to municipal solid waste emissions was negative, which suggested that an increase in FDI inflows and the literacy rate was likely to reduce CH_4 emissions from municipal solid waste and vice versa. The R-squared value of model 1 was 0.86 which meant that the independent variables used in the model explained the variation of the dependent variable very well. Regarding model 2, CH_4 emissions generated from industrial solid wastes in Saudi Arabia had a positive relationship with GDP per capita, urban population, and FDI inflows. However, the relationship between the unemployment rate and industrial solid waste emissions was negative, meaning that a decrease in the unemployment rate is likely to increase CH_4 emissions from industrial solid wastes. An R-squared value of 0.90 suggested that the independent variables used in model 2 mostly present the variations of the dependent variable.

Table 7. Co-integrating equation for model 1.

Dependent Variable: MSW			
R-Squared Value: 0.86			
Explanatory Variable	**Coefficient**	**Standard Errors**	***t*-Statistics**
Constants	4.85	0.92	5.29
GDPPC	0.0003	8.47×10^{-5}	3.09
UPOP	5.07×10^{-6}	1.39×10^{-6}	3.66
FDI	-1.22×10^{-10}	3.91×10^{-11}	−3.12
LR	-0.096	0.08	−1.15

Table 8. Co-integrating equation for model 2.

Dependent Variable: ISW			
R-Squared Value: 0.90			
Explanatory Variable	**Coefficient**	**Standard Errors**	***t*-Statistics**
Constants	−1.57	2.48	−0.63
GDPPC	0.001	0.0003	3.96
UPOP	4.34×10^{-6}	5.2×10^{-6}	0.82
FDI	1.67×10^{-10}	1.29×10^{-10}	1.29
UR	−1.18	1.69	−0.69

3.1.3. Short- and Long-Run Granger Causality (GC) Tests

This study adopted the Granger causality tests to explore how independent or explanatory variables (e.g., GDP per capita, urban population, FDI inflows, literacy rates,

and unemployment rates) are contributing to CH_4 emissions from municipal and industrial solid wastes both in the short-run and long-run. One of the advantages of Granger causality tests is that they examine the direction of causality between the dependent and independent variables. F-statistics were used to understand the significance of variables to cause an event in the short-run while *t*-statistics were used for long-run causality tests [41]. Tables 9 and 10 present the results of short- and long-run causality tests for models 1 and 2, respectively.

Table 9. Model 1: Short- and long-run causality test results.

	Short-Run GC–*F* Statistics					Long-Run GC-*t* Statistics
	Ln (MSW)	**Ln (GDPPC)**	**Ln (UPOP)**	**Ln (FDI)**	**Ln (LR)**	**Error Correction Term (ECT)**
Ln (MSW)	-	9.55 *** (0.003)	13.37 (0.0007)	9.72 (0.003)	1.33 (0.26)	−2.36 ** (0.02)
Ln (GDPPC)	1.30 (0.26)	-	1.62 (0.21)	1.38 (0.25)	0.54 (0.47)	3.09 *** (0.003)
Ln (UPOP)	3.02 * (.09)	4.07 ** (0.05)	-	0.24 (0.63)	0.39 (0.53)	3.66 *** (0.001)
Ln (FDI)	3.31 * (0.08)	9.05 *** (0.004)	1.50 (0.23)	-	7.26 *** (0.01)	−3.12 *** (0.003)
Ln (LR)	0.06 (0.81)	0.45 (0.51)	0.08 (0.79)	0.09 (0.76)	-	−1.15 (0.26)

Note: Probability value '*p*' is presented in parenthesis, and *, **, and *** show significance at 0.1, 0.05, and 0.001 levels, respectively.

Table 10. Model 2: Short- and long-run causality test results.

	Short-Run GC–*F* Statistics					Long-Run GC-*t* Statistics
	Ln (ISW)	**Ln (GDPPC)**	**Ln (UPOP)**	**Ln (FDI)**	**Ln (UR)**	**Error Correction Term (ECT)**
Ln (ISW)	-	15.69 *** (0.0003)	0.68 (0.41)	1.66 (0.20)	0.48 (0.49)	12.45 *** (0.000)
Ln (GDPPC)	0.24 (0.63)	-	4.00 ** (0.05)	4.36 ** (0.04)	1.63 (0.21)	3.96 *** (0.0003)
Ln (UPOP)	0.59 (0.45)	2.72 * (0.10)	-	0.44 (0.51)	3.76 * (0.06)	0.82 (0.41)
Ln (FDI)	4.15 ** (0.05)	8.92 *** (0.004)	1.80 (0.19)	-	0.03 (0.87)	1.29 (0.20)
Ln (UR)	0.01 (0.91)	0.25 (0.62)	1.33 (0.25)	1.09 (0.30)	-	−0.70 (0.49)

Note: Probability value '*p*' is presented in parenthesis, and *, **, and *** show significance at 0.1, 0.05, and 0.001 levels, respectively.

The results of the Granger causality test for model 1 showed that GDP per capita, urban population, and FDI inflows had both short- and long-run causal relationships with municipal solid waste emissions and these relationships are significant at 0.001 level (Table 9). In contrast, only GDP per capita had a short- and long-run causal relationship with industrial solid waste emissions (Table 10). The Granger causality test of Model 1 showed that there was a unidirectional short-run causal relationship running from GDP per capita to urban population, FDI inflows, and literacy rate. It also showed that literacy rates caused FDI inflows in the short run. Municipal solid waste emissions had a bi-directional short-run causal relationship with urban population and FDI inflows. This implies that the urban population and FDI inflow cause emissions in the short-run, and vice versa. The results of the Granger causality test for model 2 are presented in Table 10. The results show that GDP per capita had a bidirectional causal relationship with both urban population and FDI inflows in the short run. Results also showed that the unemployment rate has a causal relationship with urban population while there is a causal relationship running from industrial solid waste emissions to FDI inflows. These findings imply that GDP per capita has a strong- and long-run relationship with both municipal and industrial solid waste emissions and the development of a zero-waste economy is crucial for Saudi Arabia to reduce emissions from the solid waste sector.

3.2. Historical CH_4 Emission from MSW and Industrial Waste and Predicted Future Emission

The results of calculations of methane emission from 1990 to 2050 are presented in Figure 5. Methane emission from MSW and industrial waste is presented separately to facilitate a clear understanding of the contributions made by the municipal and industrial

waste sectors. Generally, an increasing pattern of methane emission from total waste was observed at an average annual rate of 5.53% between 1990 and 2019, and 5.13% between 2020 and 2050. Methane generation from total waste is projected to reach about 4000 Gg by the end of the year 2050, which is an increase of 370% compared to methane emitted in 2019. When considering only MSW, methane emission was impacted by the variation of the population. Figure 5 presents the historical methane emission (1990–2019) from MSW for medium variant population and that of the projected methane emission (2020 to 2050) for low, medium, and high variations of the population [39]. It was observed that both low and high variant populations caused a maximum of 5% variation (more specifically, 4.99% for low variant and 4.69% for high variant) in methane generation compared to the medium variant population. The maximum variation of methane generation due to population occurred in the year 2050. The variation of the population was considered one of the important factors in projecting methane emission due to its direct association in MSW generation and thus methane emission. Other factors, such as the fraction of DOC and waste component composition in MSW stream, are also important factors but are less likely to be varied in a wide range and impact methane generation [54].

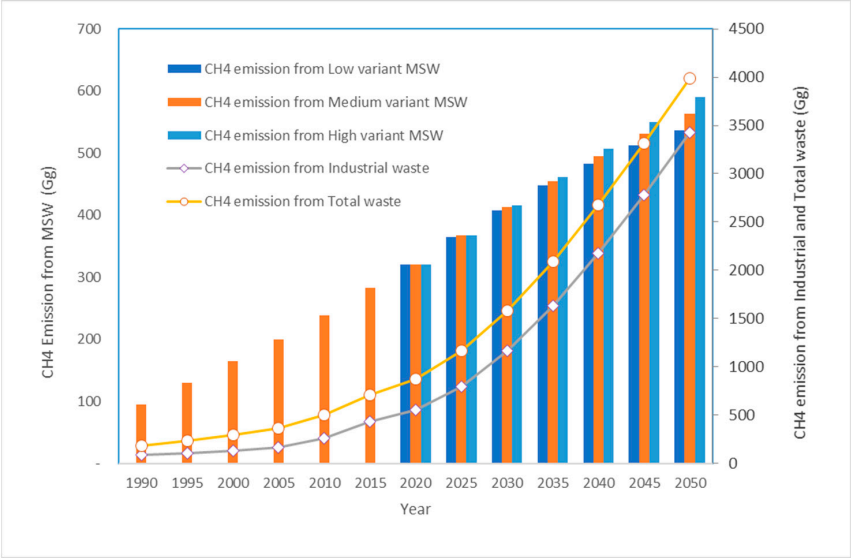


Figure 5. Historical and predicted CH_4 emission from MSW and industrial waste between 1990 and 2050 (due to population variation).

It is interesting to observe that the methane emission from MSW and industrial waste was comparable until the year 2010 (Figure 5). However, in five years (i.e., in 2015), methane emission from the industrial sector increased more than 1.5 times that of municipal solid waste. One reason of this increased emission from industrial waste is connected to the increase of GDP in those years, which was used to estimate the methane emission from the industrial waste sector [3]. The trend of the increased GDP continued until 2019 and reflected when projecting the future GDP between 2020 and 2050 (Figure 3). The projected GDP was also commensurate to an unprecedented national reform proposed by Saudi Government, VISION 2030, which was lodged in April 2016 to boost the Saudi national GDP [55]. As a result, it is obvious that a major share of total methane emission (about 86%) will be carried out by the industrial waste sector by 2050, as shown in Figure 5.

3.2.1. Impact of Urbanization on the CH_4 Emission

In the previous section, CH_4 emission from municipal solid waste was discussed for the total urban population of Saudi Arabia, which presented a general overview of the status of the historical and predicted CH_4 emission from the landfills. However, further investigation was conducted to estimate methane emissions in different major cities in Saudi Arabia to understand the growth dynamics of municipal solid waste in these cities.

Increasing urbanization is the major cause for GHG emission increment. According to a UN report, the total city area of the world would be three times the current values and three-quarters of the world population will be living in cities in 2030 [56]. As a result, GHG emission is expected to increase drastically. In Saudi Arabia, an exceptionally high increase in population was observed in some large cities including Riyadh, Madinah, Makkah, Jeddah, and Dammam between 1975 and 2015 [56]. These cities were mainly benefitted either from the kingdom's oil revenue or Islamic pilgrimage and attracted people from rural or small urban areas as well as from abroad by providing jobs. According to the United Nations [51], the population in the aforementioned major cities increased from none in 1975 to about 14.4 million in 2015, and by 2030, another 5.1 million people are expected to be living in these major cities. The trend of increased urbanization in major cities is reflected in producing higher methane emissions in these cities as shown in Figure 6. In a decade, methane emission in Riyadh is expected to reach about 70 Gg, followed by Jeddah, Makkah, Madinah, and Dammam. Methane emissions from other cities are expected to be below 10 Gg. The results presented in Figure 6 can be utilized by the local municipalities of these cities for taking any mitigation plan in reducing methane emission from the disposal of municipal solid waste.

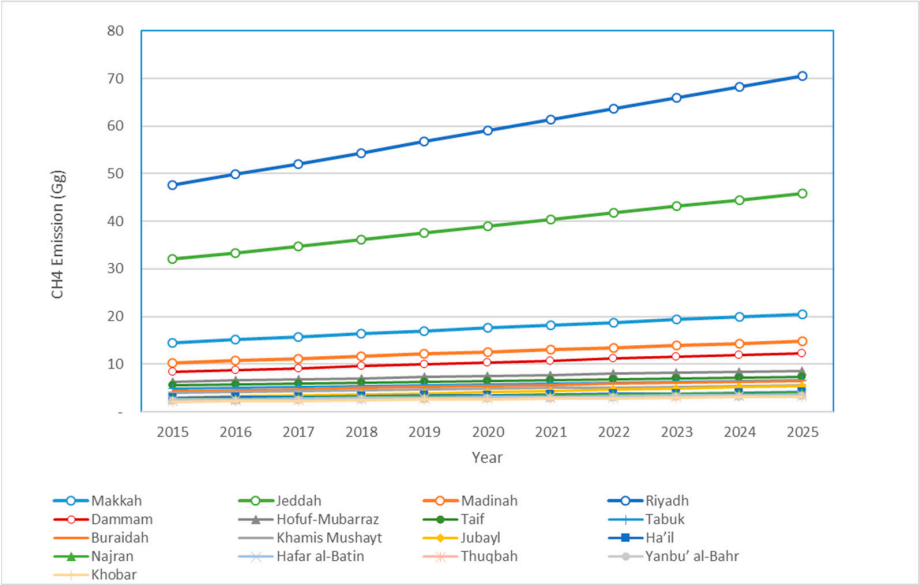


Figure 6. Historical and predicted CH_4 emission from MSW in major cities in Saudi Arabia between 2015 and 2025 (methane emission was calculated based on population data from the United Nations [51]).

3.3. Mitigation Measures to Reduce Methane Emission

Diversion of solid waste from disposing to landfill is the fundamental pathway to reduce methane emission [1]. However, rarely are there clear guidelines available in Saudi Arabia on methane reduction based on different waste disposal scenarios. Figure 7 predicts the reduction of methane emissions due to waste diversion from landfills in 16 combinations of municipal as well as industrial waste between the year 2020 and 2050. As can be seen from Figure 7a, for a 100% disposal (zero diversion) of municipal solid waste, methane emission can be reduced by 21%, if industrial waste disposal can be diverted by 25%. It was possible to further reduce the methane emission by 42% and 63% for a reduction of industrial waste disposal by 50% and 75%, respectively. The prediction clearly identifies that more attention is needed in Saudi Arabia for diverting industrial waste from landfills. In fact, the Saudi government has realized such a need of diverting industrial waste and has adopted several measures to reduce the disposal of industrial waste to landfills. According to GAS [49], in Jubail industrial area, 34% of industrial waste was

recycled in 2010, which increased to 54% in 2018; 41% of the industrial waste was landfilled in 2010, which decreased to 34% in 2018.

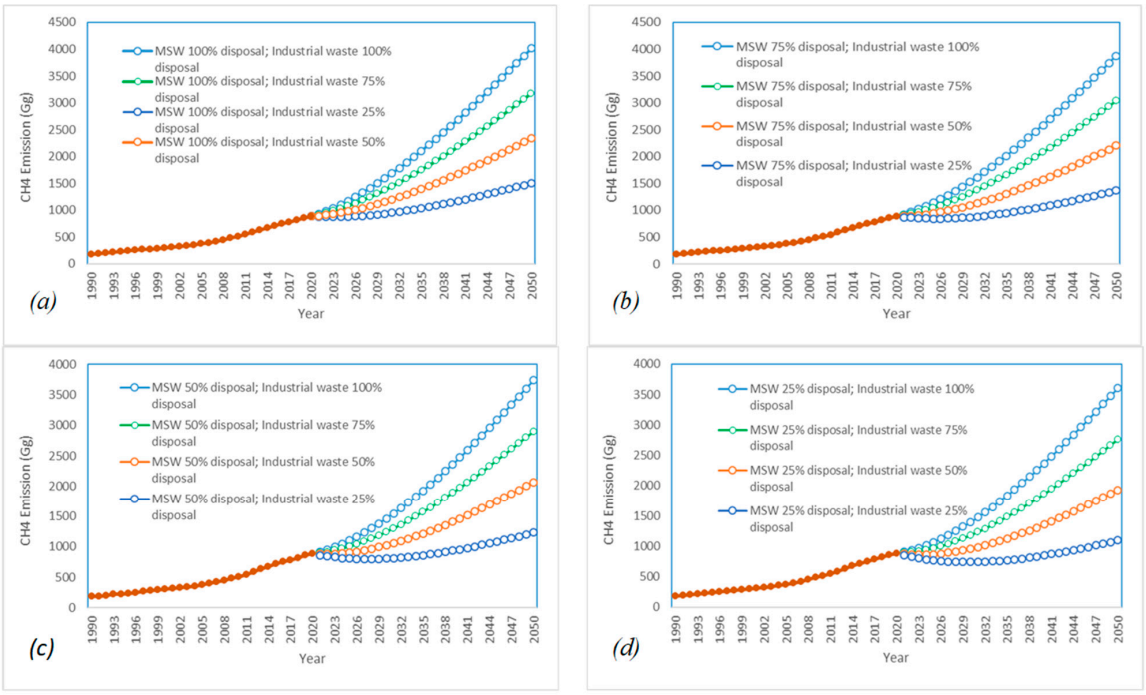


Figure 7. Impact of waste diversion from landfills on CH_4 emission between 2020 and 2050 (**a**) diversion combinations of MSW of 0% with industrial waste of 0%, 25%, 50%, and 75%, respectively (**b**) diversion combinations of MSW of 25% with industrial waste of 0%, 25%, 50%, and 75%, respectively (**c**) diversion combinations of MSW of 50% with industrial waste of 0%, 25%, 50%, and 75%, respectively (**d**) diversion combinations of MSW of 75% with industrial waste of 0%, 25%, 50%, and 75%, respectively.

It is obvious from Figure 7b–d that more reduction of methane emission is possible when MSW is also diverted from the landfill. However, the reduction of methane emission is more sensitive to industrial waste diversion compared to municipal waste. The phenomenon is presented in Figure 8. A sensitivity analysis was carried out to identify which waste diversion is crucial to the reduction of methane emission by assuming 50% disposal of both types of waste as the standard practice. It was observed (from Figure 8) that for a reduction of 25% disposal, emission from industrial waste was reduced by 38%, which was 27% for municipal solid waste. The findings again iterated that recycling and other types of mitigation measures will be more effective in reducing the methane emission in Saudi Arabia if applied to industrial waste.

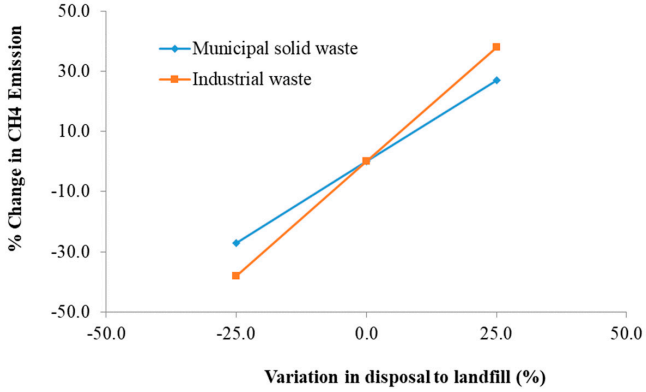


Figure 8. Sensitivity analysis of methane emission to waste diversion.

Achievement of the above-mentioned disposal reduction is possible by utilizing several mitigation initiatives. For example, adaptation of 4R (i.e., reduce, reuse recycle, and recovery) approach could generate less waste and consequently less methane gas [57]. Waste-to-energy (WTE) tools such as incineration, pyrolysis, refuse derived fuel (RDF), or anaerobic digestion with biogas recovery approach could be implemented to reduce methane emissions in Saudi Arabia. Energy content of waste could be directly converted to steam or electricity through WTE technology [58]. Electricity and heat generation efficiencies for WTE systems were reported to be in the range of 18~35% and 63~78%, respectively. However, simultaneous production of power and heat was reported to have 83% efficiency [59–61]. Combustion efficiency of 25% was assumed by some reports in calculating the WTE for Saudi Arabia [62]. Recent studies using multi-criteria analysis done for the GCC countries showed that among the WTE technologies, anaerobic digestion (AD) and landfill gas recovery had the best and gasification had the worst model result [54]. The financial model analyzed the current situation of MSW sector in Saudi Arabia showed that AD and gasification WTE plants are financially profitable endeavors in terms of investment indicators, i.e., net present value (NPV), internal rate of return (IRR), modified internal rate of return (MIRR), profitability index (PI), and Levelized Cost of Waste (LCOW) [63]. Recent studies reported new technologies such as membrane, solvent absorption, adsorption, and low-temperature techniques such as cryogenic could be successfully applied for capturing methane gas [64,65].

Another innovative and promising approach for reducing methane emission is the adaptation of circular economy (CE). One of the pillars of CE is the Cradle to Cradle® (C2C) design framework for product and process design. One of the principles of this framework is "waste equals food" [66]. The perpetual flow of food/nutrients through biological and technical metabolism would reduce waste and maximize economic and ecological benefit. In this framework, materials are considered as nutrients. The perpetual flow of nutrients through biological and technical metabolism would reduce waste and maximize economic and ecological benefits [67]. CE has been implemented mostly in developed countries of North America, Europe, and Asia for waste management at different levels from policymaking to consumer awareness creation [67,68]. It is reported that it may be possible to achieve a 20–30% reduction in methane emission by adopting CE [69].

The water–energy–food (WEF) nexus approach may also be effective for Saudi Arabia in reducing methane emission. In a recent study, Foden et al. [70] applied the WEF approach at the domestic kitchen as sites where eating habits, cleaning, cooking, and disposing of waste are considered together. However, the domestic kitchen is very much influenced by the local community, regional or central government policy, geopolitical situation, and municipal and other services available in the locality in which it is situated. As mentioned previously, anaerobic digestion could be one of the most promising techniques for MSW treatments. From a WEF nexus viewpoint, MSW used as feedstock for AD is particularly desirable as it offers several benefits across energy, food, and water domains [70].

Capturing landfill gas and flaring to reduce methane emission in the atmosphere is gaining momentum in Saudi Arabia. Landfill gas collection and a flaring system has been installed in Madinah and Jeddah landfills, which is expected to reduce landfill gas of 139,108 and 355,425 metric tons of CO2 equivalent per annum, respectively [46].

4. Conclusions

The increasing trend in population, urbanization, and industrial development has been forcing similar trends in solid waste generation and greenhouse gas emissions in the Kingdom of Saudi Arabia. The collection and use of greenhouse gases emitted from solid waste management practices are still not matured in the Kingdom. This study investigated the factors driving the emissions from solid waste management and trends of them focusing on greenhouse gas emissions. A causality analysis examined the driving factors of the emissions from solid waste management of the Kingdom and revealed that the methane (CH_4) emissions from municipal solid waste are positively related with gross

domestic product (GDP) per capita and urban population, and an increase in foreign direct investment (FDI) inflows and literacy rate is likely to reduce CH_4 emissions from municipal solid waste and vice versa. The CH_4 emissions generated from industrial solid wastes have a positive relationship with GDP per capita, urban population, and FDI inflows. However, a decrease in the unemployment rate is likely to increase CH_4 emissions from industrial solid wastes. The future greenhouse gas emissions were projected under different possible socio-economic conditions. The scenario analysis based on different variations of the population revealed that the CH_4 emissions from municipal solid waste management may vary between 537 and 590 Gg, and emission from total waste may reach about 4000 Gg in 2050. The future GHG emission scenarios from solid waste management practices and the climate change mitigation opportunities having other co-benefits are expected to support relevant options including reduction, recycling, composting and waste-to-energy, and carbon capture and utilization. The industrial sector has already adopted some encouraging efforts such as recycling initiatives which have been impacting climate change mitigation positively. The circular economy approach is also getting initial momentum in the country.

Policy Implications

This study has significant policy implications for the waste sector of Saudi Arabia. For example, a causal relationship between solid waste emissions (both municipal and industrial) and GDP per capita implies that Saudi Arabia's GDP needs to be diverted towards a zero-waste economy. The causal relationship between urban population and emissions indicates that waste generation rates in Saudi cities needs to be halted and the waste management system needs to be improved to tackle the burgeoning solid waste emissions. FDI inflows also need to be channeled via a zero-waste policy so that the causal relationship between FDI inflows and municipal solid waste emissions can be decoupled.

In general, the developing countries have been suffering from the availability of relevant data to develop policies based on quantitative and objective analysis. The Kingdom of Saudi Arabia is not an exception in this regard especially for the management of greenhouse gas emissions from solid waste management practices. This study traced the main driving factors of emissions, projected the emissions for different scenarios, and highlighted some suitable climate change mitigation opportunities for the Kingdom. The results of this study will support the policymakers to understand the dynamics of the driving factors and trace the current and future contributions of solid waste management practices in national greenhouse gas inventories. The results will help to track national greenhouse gas emissions and prioritize climate change mitigation initiatives. However, the researcher community should come forward to develop appropriate quantitative analyses focusing on wide varieties of climate change mitigation options to support the policymakers.

Author Contributions: Conceptualization, S.M.R. and M.M.R.; methodology, M.A.H., M.M.R.; software, M.A.H., M.M.R.; formal analysis, M.A.H., M.M.R.; data curation, M.A.H., M.M.R., M.S.R., S.A.S., and S.R.; writing—original draft preparation, M.S.R., M.M.R.; writing—review and editing, S.M.R., M.A.H., M.M.R., M.S.R., S.A.S., and S.R.; funding acquisition, M.M.R. All authors have read and agreed to the published version of the manuscript.

Funding: The authors extend their appreciation to the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia for funding this research work through the project number IFT20047.

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: https://data.worldbank.org/country/SA (accessed on 11 February 2021).

Acknowledgments: The authors acknowledge the support received from Deanship of Scientific Research at King Faisal University (KFU), King Fahd University of Petroleum & Minerals (KFUPM), Al-Imam Mohammad Ibn Saud Islamic University, and Victoria University of Wellington.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Xin, C.; Zhang, T.; Tsai, S.B.; Zhai, Y.M.; Wang, J. An empirical study on greenhouse gas emission calculations under different municipal solid waste management strategies. *Appl. Sci.* **2020**, *10*, 1673. [CrossRef]
2. Hogland, W.; Marques, M. Sustainable waste management: International perspectives. In Proceedings of the International Conference on Sustainable Solid Waste Management, Chennai, India, 5–7 September 2007; pp. 1–8.
3. IPCC. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; IPCC: Geneva, Switzerland, 2019. Available online: https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/ (accessed on 21 January 2021).
4. Pires, A.; Martinho, G.; Chang, N.-B. Solid waste management in European countries: A review of systems analysis techniques. *J. Environ. Manag.* **2011**, *92*, 1033–1050. [CrossRef]
5. Abdoli, M.A.; Falahnezhad, M.; Behboudian, S. Multivariate Econometric Approach for Solid Waste Generation Modeling: Impact of Climate Factors. *Environ. Eng. Sci.* **2011**, *28*, 627–633. [CrossRef]
6. Daskalopoulos, E.; Badr, O.; Probert, S. Municipal solid waste: A prediction methodology for the generation rate and composition in the European Union countries and the United States of America. *Resour. Conserv. Recycl.* **1998**, *24*, 155–166. [CrossRef]
7. Hockett, D.; Lober, D.J.; Pilgrim, K. Determinants of Per Capita Municipal Solid Waste Generation in the Southeastern United States. *J. Environ. Manag.* **1995**, *45*, 205–217. [CrossRef]
8. Dong, Y.H.; An, A.K.; Yan, Y.S.; Yi, S. Hong Kong's greenhouse gas emissions from the waste sector and its projected changes by integrated waste management facilities. *J. Clean. Prod.* **2017**, *149*, 690–700. [CrossRef]
9. Ermolaev, E.; Jarvis, Å.; Sundberg, C.; Smårs, S.; Pell, M.; Jönsson, H. Nitrous oxide and methane emissions from food waste composting at different temperatures. *Waste Manag.* **2015**, *46*, 113–119. [CrossRef] [PubMed]
10. Giannakitsidou, O.; Tsagkanos, A.; Giannikos, I. Correlation of municipal solid waste production and treatment with socioeconomic indexes. *Int. J. Environ. Waste Manag.* **2016**, *18*, 303. [CrossRef]
11. Vieira, V.H.A.D.M.; Matheus, D.R. The impact of socioeconomic factors on municipal solid waste generation in São Paulo, Brazil. *Waste Manag. Res.* **2018**, *36*, 79–85. [CrossRef] [PubMed]
12. Hoornweg, D.; Bhada-Tata, P. *What a Waste: A Global Review of Solid Waste Management*; World Bank: Washington, DC, USA, 2012.
13. Chandrappa, R.; Das, D. *Solid Waste Management Principles and Practice*; Springer: Berlin/Heidelberg, Germany, 2012.
14. Rodic, L.; Scheinberg, A.; Wilson, D.C. *Solid Waste Management in the World's Cities*; Wageningen University & Research: Wageningen, The Netherlands, 2010.
15. Khan, D.; Kumar, A.; Samadder, S. Impact of socioeconomic status on municipal solid waste generation rate. *Waste Manag.* **2016**, *49*, 15–25. [CrossRef]
16. Mahees, M.; Sigayoganathan, C.; Basnayake, B. Consumption, Solid Waste Generation and Water Pollution in Pinga Oya Catchment area. *Trop. Agric. Res.* **2011**, *22*, 239. [CrossRef]
17. Lu, J.-W.; Zhang, S.; Hai, J.; Lei, M. Status and perspectives of municipal solid waste incineration in China: A comparison with developed regions. *Waste Manag.* **2017**, *69*, 170–186. [CrossRef] [PubMed]
18. Kuznets, S. Economic growth and income. *Am. Econ. Rev.* **1955**, *45*, 3–29.
19. Lee, S.; Kim, J.; Chong, W.O. The Causes of the Municipal Solid Waste and the Greenhouse Gas Emissions from the Waste Sector in the United States. *Procedia Eng.* **2016**, *145*, 1074–1079. [CrossRef]
20. Magazzino, C.; Mele, M.; Schneider, N. The relationship between municipal solid waste and greenhouse gas emissions: Evidence from Switzerland. *Waste Manag.* **2020**, *113*, 508–520. [CrossRef]
21. Namlis, K.-G.; Komilis, D. Influence of four socioeconomic indices and the impact of economic crisis on solid waste generation in Europe. *Waste Manag.* **2019**, *89*, 190–200. [CrossRef]
22. Liu, J.; Li, Q.; Gu, W.; Wang, C. The Impact of Consumption Patterns on the Generation of Municipal Solid Waste in China: Evidences from Provincial Data. *Int. J. Environ. Res. Public Heal.* **2019**, *16*, 1717. [CrossRef]
23. Trang, P.T.T.; Dong, H.Q.; Toan, D.Q.; Hanh, N.T.X.; Thu, N.T. The Effects of Socio-economic Factors on Household Solid Waste Generation and Composition: A Case Study in Thu Dau Mot, Vietnam. *Energy Procedia* **2017**, *107*, 253–258. [CrossRef]
24. Talalaj, I.A.; Walery, M. The effect of gender and age structure on municipal waste generation in Poland. *Waste Manag.* **2015**, *40*, 3–8. [CrossRef]
25. Kannangara, M.; Dua, R.; Ahmadi, L.; Bensebaa, F. Modeling and prediction of regional municipal solid waste generation and diversion in Canada using machine learning approaches. *Waste Manag.* **2018**, *74*, 3–15. [CrossRef] [PubMed]
26. Song, Q.; Li, J.; Zeng, X. Minimizing the increasing solid waste through zero waste strategy. *J. Clean. Prod.* **2015**, *104*, 199–210. [CrossRef]
27. Ari, I.; Şentürk, H. The relationship between GDP and methane emissions from solid waste: A panel data analysis for the G7. *Sustain. Prod. Consum.* **2020**, *23*, 282–290. [CrossRef]
28. Chen, Y.-C.; Wu, W.-F. Constructing an effective prevention mechanism for MSW lifecycle using failure mode and effects analysis. *Waste Manag.* **2015**, *46*, 646–652. [CrossRef] [PubMed]
29. Yang, D.; Xu, L.; Gao, X.; Guo, Q.; Huang, N. Inventories and reduction scenarios of urban waste-related greenhouse gas emissions for management potential science of the total environment inventories and reduction scenarios of urban waste-related greenhouse gas emissions for management potential. *Sci. Total Environ.* **2018**, *626*, 727–736. [CrossRef] [PubMed]

30. Turan, N.G.; Çoruh, S.; Akdemir, A.; Ergun, O.N. Municipal solid waste management strategies in Turkey. *Waste Manag.* **2009**, *29*, 465–469. [CrossRef]
31. Lima, R.M.; Santos, A.H.; Pereira, C.R.; Flauzino, B.K.; Pereira, A.C.O.; Nogueira, F.J.; Valverde, J.A.R. Spatially distributed potential of landfill biogas production and electric power generation in Brazil. *Waste Manag.* **2018**, *74*, 323–334. [CrossRef] [PubMed]
32. USEPA. *Landfill Methane Outreach Program (LMOP), Landfill Gas Energy Project Development Handbook*; USEPA: Washington, DC, USA, 2020.
33. Jha, A.K.; Sharma, C.; Singh, N.; Ramesh, R.; Purvaja, R.; Gupta, P.K. Greenhouse gas emissions from municipal solid waste management in Indian mega-cities: A case study of Chennai landfill sites. *Chemosphere* **2008**, *71*, 750–758. [CrossRef]
34. Kormi, T.; Ali, N.B.H.; Abichou, T.; Green, R. Estimation of landfill methane emissions using stochastic search methods. *Atmos. Pollut. Res.* **2017**, *8*, 597–605. [CrossRef]
35. Themelis, N.J.; Ulloa, P.A. Methane generation in landfills. *Renew. Energy* **2007**, *32*, 1243–1257. [CrossRef]
36. Silva, T.R.; Barros, R.M.; Filho, G.L.T.; Dos Santos, I.F.S. Methodology for the determination of optimum power of a Thermal Power Plant (TPP) by biogas from sanitary landfill. *Waste Manag.* **2017**, *65*, 75–91. [CrossRef]
37. Lucernoni, F.; Capelli, L.; Sironi, S. Comparison of different approaches for the estimation of odour emissions from landfill surfaces. *Waste Manag.* **2017**, *63*, 345–353. [CrossRef]
38. World Bank. Data Bank of World Development Indicators 2020. Available online: https://data.worldbank.org/country/SA (accessed on 5 November 2020).
39. United Nations. World Population Prospects 2019: Methodology of the United Nations Population Estimates and Projections (ST/ESA/SER.A/425). Department of Economic and Social Affairs, Population Division 2019. Available online: https://population.un.org/wpp/Publications/Files/WPP2019_Methodology.pdf (accessed on 5 November 2020).
40. Grazhdani, D. Assessing the variables affecting on the rate of solid waste generation and recycling: An empirical analysis in Prespa Park. *Waste Manag.* **2016**, *48*, 3–13. [CrossRef]
41. Hasan, A.; Frame, D.J.; Chapman, R.; Archie, K.M. Emissions from the road transport sector of New Zealand: Key drivers and challenges. *Environ. Sci. Pollut. Res.* **2019**, *26*, 23937–23957. [CrossRef]
42. Hasan, M.A. *Understanding the Costs, Benefits, Mitigation Potentials and Ethical Aspects of New Zealand's Transport Emissions Reduction Policies by Md Arif Hasan*; Victoria University of Wellington: Auckland, New Zealand, 2020.
43. Arltová, M.; Fedorová, D. Selection of unit root test on the basis of length of the time series and value of AR(1) parameter. *Statistika* **2016**, *96*, 47–64.
44. Azlina, A.; Law, S.H.; Mustapha, N.H.N. Dynamic linkages among transport energy consumption, income and CO2 emission in Malaysia. *Energy Policy* **2014**, *73*, 598–606. [CrossRef]
45. Gharaibeh, E.S.; Haimour, N.M.; Akash, B.A. Evaluation of Current Municipal Solid Waste Practice and Management for Al-Ahsa, Saudi Arabia. *Int. J. Sustain. Water Environ. Syst.* **2011**, *2*, 103–110. [CrossRef]
46. CDM. Clean Development Mechanism. *United Nations Framework Convention on Climate Change 2020*. Available online: https://cdm.unfccc.int/Projects/DB/DNV-CUK1343105327.39/view (accessed on 5 November 2020).
47. Adhikari, B.K.; Barrington, S.; Martinez, J.; King, S. Characterization of food waste and bulking agents for composting. *Waste Manag.* **2008**, *28*, 795–804. [CrossRef] [PubMed]
48. Khan, M.S.M.; Kaneesamkandi, Z. Biodegradable waste to biogas: Renewable energy option for the Kingdom of Saudi Arabia. *Int. J. Innov. Appl. Stud.* **2013**, *4*, 101–113.
49. GAS. General Authority of Statistics in Saudi Arabia. Percentage of Disposal Methods for Industrial Waste in Saudi Arabia (Jubail) during the Period 2010–2018. Available online: https://www.stats.gov.sa/sites/default/files/percentage_of_disposal_methods_for_industrial_waste_in_saudi_arabia.pdf (accessed on 5 November 2020).
50. Price Water Cooper. The World in 2050- will the shift in Global Economic Power Continue? 2020. Available online: https://www.pwc.com/gx/en/issues/the-economy/assets/world-in-2050-february-2015.pdf (accessed on 5 November 2020).
51. United Nations. *World Urbanization Prospects: The 2018 Revision*; United Nations: New York, NY, USA, 2018.
52. GAS. General Authority of Statistics in Saudi Arabia. Per Capita Waste Generation in Saudi Arabia during the Period 2010–2018. Available online: https://www.stats.gov.sa/en/node/10131 (accessed on 5 November 2020).
53. Sedek, E.-S.; Seif, A.; Hakami, B.A. Household solid waste composition and management in jeddah city, saudi arabia: A planning model pollution view project construction material view project household solid waste composition and management in Jeddah city, Saudi Arabia: A planning model. *Int. Res. J. Environ. Sci. Int. Sci. Congr. Assoc.* **2015**, *4*, 1–10.
54. Alsabbagh, M. Mitigation of CO2e Emissions from the Municipal Solid Waste Sector in the Kingdom of Bahrain. *Climate* **2019**, *7*, 100. [CrossRef]
55. VISION 2030. The Saudi 2030 Vision Theme 2020. Available online: https://vision2030.gov.sa/en (accessed on 21 January 2021).
56. UN-Habitat. Future Saudi Cities Programme, Saudi Cities Report 2019. Available online: https://unhabitat.org/sites/default/files/2020/05/saudi_city_report.english.pdf (accessed on 17 November 2020).
57. Wang, J.; Li, Z.; Tam, V.W. Identifying best design strategies for construction waste minimization. *J. Clean. Prod.* **2015**, *92*, 237–247. [CrossRef]
58. Luz, F.C.; Rocha, M.H.; Lora, E.E.S.; Venturini, O.J.; Andrade, R.V.; Leme, M.M.V.; Del Olmo, O.A. Techno-economic analysis of municipal solid waste gasification for electricity generation in Brazil. *Energy Convers. Manag.* **2015**, *103*, 321–337. [CrossRef]

59. Chen, Y.-C. Evaluating greenhouse gas emissions and energy recovery from municipal and industrial solid waste using waste-to-energy technology. *J. Clean. Prod.* **2018**, *192*, 262–269. [CrossRef]
60. Kamuk, B.; Haukohl, J. *Waste to Energy in Low and Medium Income Countries*; ISWA: Vienna, Austria, 2013.
61. Rehan, M.; Nizami, A.-S.; Asam, Z.-U.-Z.; Ouda, O.K.; Gardy, J.; Raza, G.; Naqvi, M.; Ismail, I.M. Waste to Energy: A Case Study of Madinah City. *Energy Procedia* **2017**, *142*, 688–693. [CrossRef]
62. Ouda, O.K.; Cekirge, H.M.; Raza, S.A. An assessment of the potential contribution from waste-to-energy facilities to electricity demand in Saudi Arabia. *Energy Convers. Manag.* **2013**, *75*, 402–406. [CrossRef]
63. Hadidi, L.A.; Omer, M.M. A financial feasibility model of gasification and anaerobic digestion waste-to-energy (WTE) plants in Saudi Arabia. *Waste Manag.* **2017**, *59*, 90–101. [CrossRef]
64. Sodeifian, G.; Raji, M.; Asghari, M.; Rezakazemi, M.; Dashti, A. Polyurethane-SAPO-34 mixed matrix membrane for CO2/CH4 and CO2/N2 separation. *Chin. J. Chem. Eng.* **2019**, *27*, 322–334. [CrossRef]
65. Yaman, C.; Anil, I.; Alagha, O. Potential for greenhouse gas reduction and energy recovery from MSW through different waste management technologies. *J. Clean. Prod.* **2020**, *264*, 121432. [CrossRef]
66. Visser, W.; McDonough, W.; Braungart, M. *Cradle to Cradle*; Greenleaf Publishing Limited: Sheffield, UK, 2013.
67. Winans, K.; Kendall, A.; Deng, H. The history and current applications of the circular economy concept. *Renew. Sustain. Energy Rev.* **2017**, *68*, 825–833. [CrossRef]
68. Liu, Z.; Adams, M.; Cote, R.P.; Chen, Q.; Wu, R.; Wen, Z.; Liu, W.; Dong, L. How does circular economy respond to greenhouse gas emissions reduction: An analysis of Chinese plastic recycling industries. *Renew. Sustain. Energy Rev.* **2018**, *91*, 1162–1169. [CrossRef]
69. Iaquaniello, G.; Centi, G.; Salladini, A.A.; Palo, E.; Perathoner, S. Waste to Chemicals for a Circular Economy. *Chem. A Eur. J.* **2018**, *24*, 11831–11839. [CrossRef] [PubMed]
70. Foden, M.; Browne, A.L.; Evans, D.M.; Sharp, L.; Watson, M. The water–energy–food nexus at home: New opportunities for policy interventions in household sustainability. *Geogr. J.* **2018**, *185*, 406–418. [CrossRef]