CHAPTER 4

RESULTS AND DISCUSSION

4.1 The input parameters for IPCC Waste Model

In this study, the IPCC waste model was used to estimate CH_4 generation from JSL. This model had been used by many researchers to create national level CH_4 emissions inventory such as for Africa (Couth *et al.*, 2011), Thailand (Wangyao *et al.*, 2010) and Panama (Weitz *et al.*, 2008). The input parameters used for JSL were collected directly from the field, as well as, from literatures. Some of the values were generated from USEPA (2004) formulas and default values of IPCC (2006) to obtain a good correlation between the calculated and measured CH_4 data. Subsequently, these values were used to calculate the estimated CH_4 generation for JSL.

As shown in **Table 4.1**, the key parameters that were subjected to change and analysed were the degradable organic carbon (DOC), fraction of DOC decomposed (DOC_f), decay rate (k), fraction of CH_4 in LFG (F) and methane correction factor (MCF). Each parameter was calculated three times using the minimum and the maximum value from IPCC and USEPA range, as well as, the site-specific values. The best fitting parameter and its range was later determined using the error function analysis. Thus, a site-specific value as well as the maximum and minimum range of each parameter was created for JSL. This similar method was used by Couth *et al.,* (2011) in modelling GHGs emissions in Africa.

Table 4.1: Values used in IPCC Waste Model for bulk waste approach

No.	Parameters	Minimum	Site-Specific	Maximum
1.	Fraction of Degradable Organic Carbon (DOC)	0.12	0.14	0.28
2.	Fraction of DOC decomposed (DOC_f)	0.56	0.77	0.91
3.	Decay rate (k) , y^{-1}	0.15	0.09	0.20
4.	Fraction of CH_4 in LFG (F)	0.5	0.6	0.7
5.	Methane Correction Factor (MCF)	0.5	0.6	0.8

Table 4.1 depicts the parameters used in the **bulk waste approach**. It was deduced that in most parameters the minimum and maximum values were below and above the site specific value. According to IPCC (2006), these ranges were found to be the most suitable for tropical climate. Thus, Penteado *et al.*, (2012) had used the IPCC Waste Model for calculating CH_4 emissions from a Brazilian landfill, Wangyao *et al.*, (2010) for Thailand and Weitz *et al.*, (2008) for Panama. However, in the decay rate the site specific value was lower than the minimum value suggested in the above table. The lower rate is assigned to this homogenous decay rate for bulk waste approach with implication that the LFG production increases with time after burial of waste (Amini & Reinhart, 2011; Cruz & Barlaz, 2010).

For the **waste composition approach**, the same criteria using the minimum, maximum and site specific value for each parameter was applied. The values are tabulated in **Table 4.2**. Only three waste composition categories are enlisted in JSL as it does not

take into consideration the garden and park waste. Food waste, paper or textile and wood or straw are the three main categories used. The DOC, DOC_f, F and MCF are fractional values without any units while the decay rate, k has a unit of y^{-1} (IPCC, 2006).

Table 4.2: Values used in IPCC Waste Model for waste composition approach

No.	Type of waste		DOC	DOC_f	$k\ (y^{-1})$	F	MCF
1.	Food Waste	Minimum	0.08	0.50	0.14	0.5	0.5
		Site-Specific	0.15	0.58	0.40	0.6	0.6
		Maximum	0.20	0.65	0.70	0.7	0.8
2..	Paper or Textile	Minimum	0.20	0.30	0.06	0.5	0.5
		Site-Specific	0.40	0.40	0.07	0.6	0.6
		Maximum	0.45	0.56	0.25	0.7	0.8
3.	Wood or Straw	Minimum	0.39	0.17	0.03	0.5	0.5
		Site-Specific	0.43	0.33	0.04	0.6	0.6
		Maximum	0.46	0.61	0.05	0.7	0.8

Each data were derived from the IPCC as inventory for Tropical countries, as well as, from other literatures (Penteado *et al.*, 2012; Amini & Reinhart, 2011; Cruz & Barlaz, 2010; Machado *et al.*, 2009; Thompson *et al.*, 2009). Subsequently, using the values from **Tables 4.1** and **4.2** CH_4 generated was estimated using the IPCC Waste Model.

4.2 Measured LFG from JSL

The LFG$_{CH4}$ flow rate and yearly tonnage were proportional and have a significant correlation coefficient of more than 90% ($R^2 = 0.96$) (**Table 4.3**). The flow rate readings were recorded from 2010 onwards. The increase in percentage of volume over volume fraction of CH_4 generated is significant for higher CH_4 production yield and energy recovery (Sormunen *et al.*, 2013; Machado *et al.*, 2009; Weitz *et al.*, 2008). Similar results have been reported by Penteado, *et al.,* (2012) in a study at a Brazilian landfill. **Table 4.3** shows the flow rate measurements from JSL.

Table 4.3: CH$_4$ fraction and LFG$_{CH4}$ flow rate in JSL

Year	% CH$_4$ (vol. of CH$_4$ / vol. of total LFG)	LFG$_{CH4}$ (Nm^3/h)
2010	50.38	1663
2011	53.31	1866
2012	60.36	2013
2013	67.41	2360

4.3 Waste data

Waste data from JSL was collected from January 2007 to December 2013 and ranged from 569,561 to 826,986 tonnes per year (**Table 4.4**). The MSW landfilled showed a steady increase due to waste generation increased as more urbanization and development took place. There is also a significant hike of 11% from year 2011 to 2012

because JSL received more MSW during that period. Therefore, this resulted in the opening of new cells in Phase 3 and Phase 4 of JSL

Table 4.4: MSW disposed into JSL from 2007 to 2013

Year	Tonnes per year
2007	569,561
2008	730,548
2009	752,547
2010	740,064
2011	736,644
2012	819,840
2013	826,986

In the IPCC's National GHG Inventories (IPCC, 2006), waste composition was identified as one of the main factor influencing emissions from SWDs. The presence of different amount of DOC and fossil carbon in each waste type contributed to this factor (IPCC, 2006). Waste composition obtained from the manual sorting is shown in **Table 4.5**. It indicates the component categories and complete definition of the composition. The highest percentage of waste is food waste which is about 49% followed by plastic at 20% and wood at 11%. The amount of food waste is similar to the Malaysian MSW average (KPKT, 2013), Bukit Tagar Sanitary Landfill in Rawang, Malaysia (Beh, 2012), urban Africa (Couth *et al*., 2011) as well as, to Indian megacities like Chennai

and Kolkata (Jha *et al.,* 2008). It also coincides with the MSW composition of food waste for middle income and low income countries (World Bank, 2012).

Table 4.5: Description of waste component categories in JSL

Categories	Description	Percentage (of wet weight)
Paper	Hard paper, soft paper, cardboard, newsprint and magazines	5%
Food waste	All food waste	49%
Wood	Wood, garden waste (Branches, leaves, twigs, grass) and other plant material	11%
Textile	All type of textile	6%
Plastic	Hard plastic, soft plastic, PET bottles	20%
Metal	Aluminium cans, metal, tin and alloy	2%
Glass	All glass	6%
Other materials	Rock, sand, dirt, ceramics, plaster, electronic wires and polystyrene	1%

In Agamuthu *et al.*, (2009), it was established that the trend in plastic consumption had decreased between 1970 to 1990 due to an economic slowdown however, increased again in early 2000. The shot up come about the introduction of more plastic- and paper- based hygienic packaging. However, this scenario is in contrast with Indian megacity Kolkata, in which the plastic content in MSW that had increased in the past has subsequently stabilized due to the budding awareness and recycling of plastics (Jha *et al.*, 2008). From the high amount of organics and plastic (**Table 4.5**), it also clearly apparent that there were no sorting or separating activities that have been carried out

before the MSW is landfilled. Thus, more awareness is needed among the Malaysians to actively participate in the recycling wheel.

Nevertheless, the low percentage of paper (5%) and metal (2%) shows that these two materials are probably separated and recycled before it reaches the landfill. In Malaysia, the diversion of these two items from the waste stream fetches good returns for money. Paper and metal is priced between RM0.18 to RM0.60 per kg and RM4.50 to RM6.00 per kg, respectively (KPKT, 2012; PEM, 2008). Additionally, other inert materials like polystyrene were also in the landfill but it only contribute to about 1% of the total MSW content.

4.4 The bulk waste and waste composition approach

The comparative results of these two approaches and the measured CH_4 from JSL are shown in **Figure 4.1**. For the bulk waste approach the tonnage for each year was used as a whole, while for the waste composition approach, only the organic fraction of the MSW was considered for CH_4 generation.

From the results obtained, both approaches used do not perfectly match the measured CH_4 from JSL. CH_4 generation by the model in both approaches was overestimated by 13% to 58% (**Fig.4.1**). Generally, this model's overestimation was in agreement with other research findings by Penteado *et al.* (2012) and Abushammala *et al.*, (2011). Wangyao *et al.* (2010), who used the IPCC Waste Model for CH_4 emission studies in Thailand, scored a faired result compared to the field measured. The variation in model results as compared of measured data from the landfill is due to limited amount of

measured data available (Scharff & Jacobs; 2006), age of refuse (Cruz & Barlaz, 2010; Wangyao *et. al.*, 2010; Machado *et al.*, 2009) and discrepancy in input parameters (Thompson *et al.*, 2009).
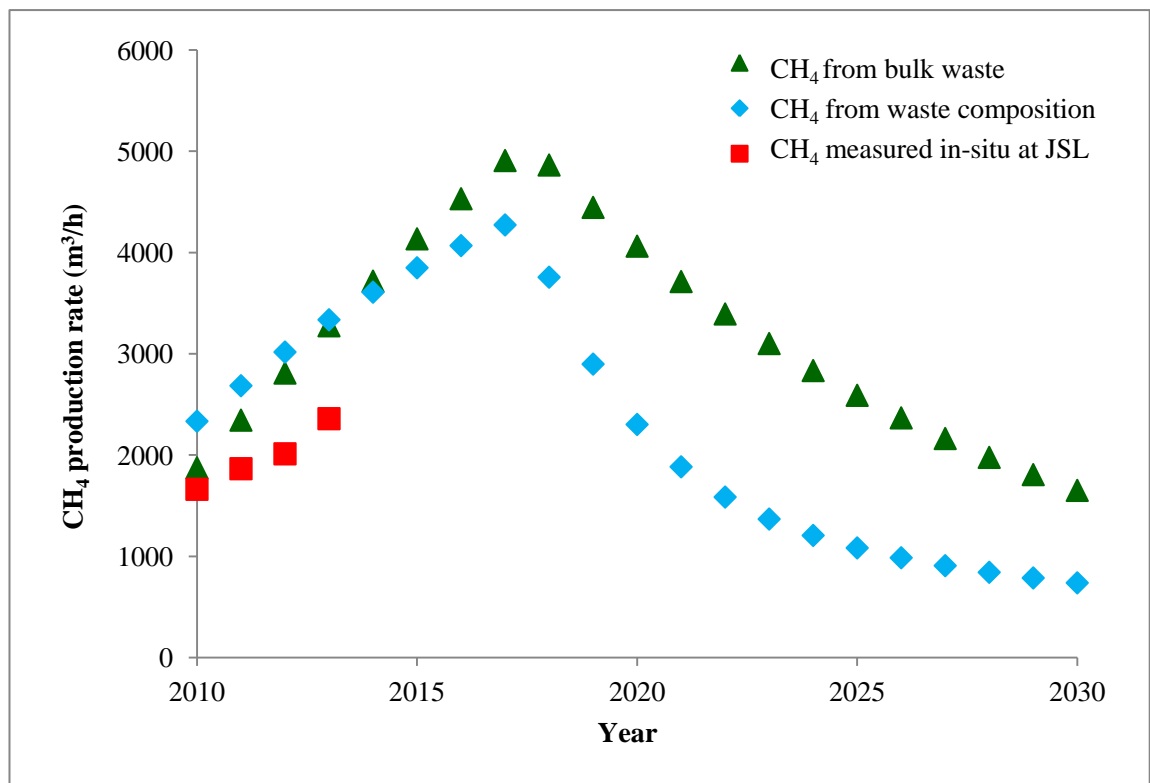

Figure 4.1: Comparison between measured and calculated CH_4 production

In the case of waste composition approach, higher CH_4 generation compared to the bulk waste approach was estimated in the first few years of landfilling. This initial increase could be due to the fact that food waste which dominates the waste composition produced more CH_4 as it decomposed promptly compared to other materials. A study by Cruz and Barlaz (2010) on decay rates of waste components supports the theory that the rapid increase in CH_4 production is due to food waste degradation.

Peak CH_4 production for both approaches was attributed after 10 years of landfilling. The CH_4 production rate was estimated to 4909 m^3/h and 4273 m^3/h respectively for bulk waste and waste composition approach. In both cases, the model estimates were very close with a CH_4 production difference of only 3.67 Gg which is a suitable time for continuous LFG collection system to be emphasized and operated in landfills (Tolaymat *et. al.*, 2010). However after 10 years in operation, the CH_4 production from waste composition approach plunged more rapidly as compared to the bulk waste approach. This, points to the half-life of food waste which is much shorter as compared to the other waste components (Penteado *et al.*, 2012; Cruz & Barlaz, 2010). Food waste which has a short half-life due to its fast decay rate is unable to continuously yield more CH_4 after reducing its mass by half.

The highest difference in CH_4 production rate between these two approaches was 58%. Therefore, to determine the significant difference between the approaches, an analysis of variance (ANOVA) was performed. A one way ANOVA using a general linear model showed that the Fisher's *F*-test with $F_{stat} = 4.31$ was found to be greater than the tabulated *F* value ($F_{crit} = 4.05$) at 95% confidence interval. In addition, the lower probability value (*p*-value > *F*=0.04) also indicated that there is significant difference in the CH_4 production rate between both the approaches used.

4.4.1 Influence of DOC

The influence of DOC on CH_4 production obtained from both bulk waste and waste composition approach are shown in **Figures 4.2** and **4.3**. In the bulk waste approach

(**Fig. 4.2**), the maximum, minimum and site specific DOC values used were 28%, 12% and 14%, respectively. All three values clearly showed an overestimation of the calculated CH_4 compared to the *in-situ* measured CH_4.

A difference of 3-20% was obtained for the minimum and site-specific DOC values. These values can be considered as the uncertainty limits of the model analogous with Pentendo *et al.,* (2012) who had a ±15% uncertainty limits in his study and IPCC Guidelines (IPCC, 2006) ranged between ±20% uncertainty limit. On the contrary, there is a huge difference for the maximum DOC value used; it soared above 150% in difference (**Fig. 4.2**). In this case, it is mandatory to underline that the 28% DOC is too unlikely to be achieved unless materials with high DOC values are collected and landfilled separately (Pentendo *et al*., 2012). In general, developing countries would have higher DOC as poor waste segregation is often practiced. High value of DOC is from high content of paper, textile and wood in the waste stream (IPCC, 2006).
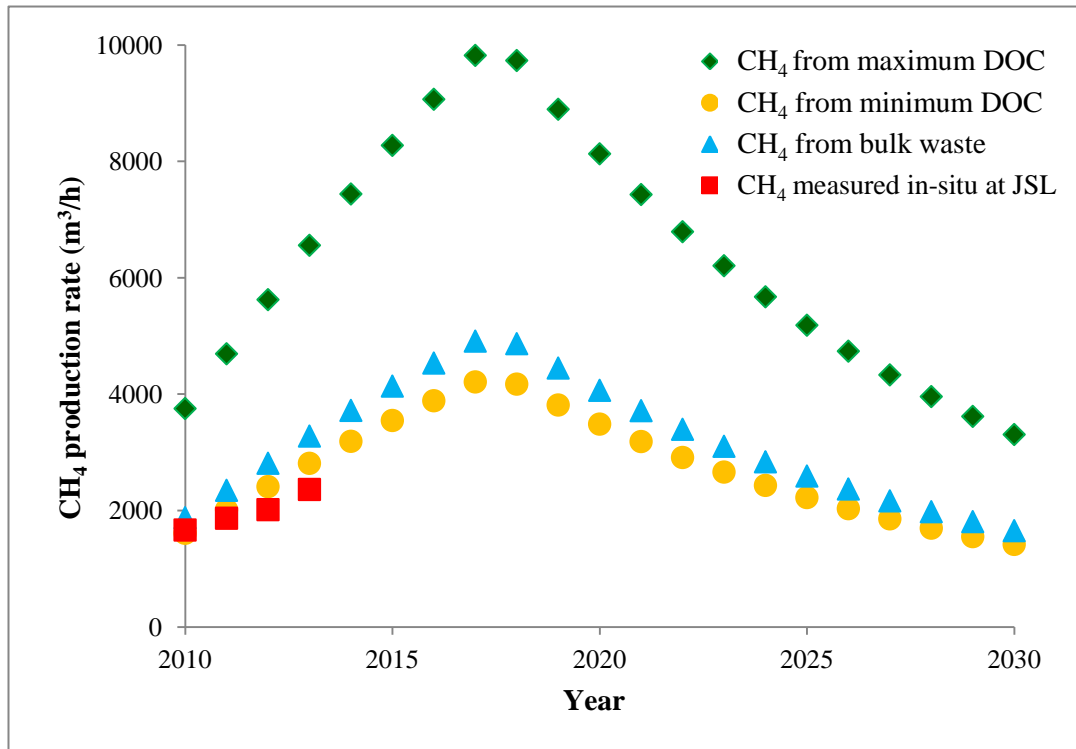
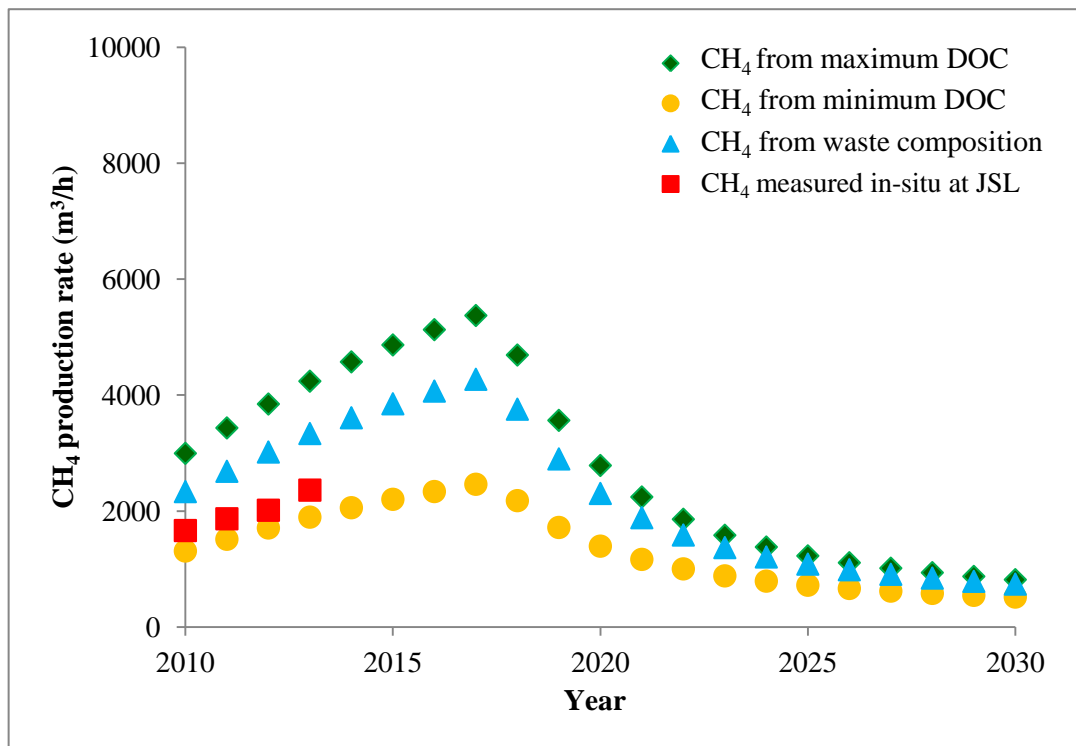**Figure 4.2:** CH_4 generation from different DOC ranges using the bulk waste approach

Figure 4.3: CH_4 generation from different DOC ranges using the waste composition approach

In terms of the waste composition approach (**Fig.4.3**), the calculated CH_4 were more in agreement with the measured CH_4 as compared to the bulk waste approach. The maximum and site specific DOC values used overestimated CH_4 production by 40-90% but the minimum DOC value used underestimated the calculated CH_4 by 20%. Hence, in this case the minimum DOC value is in a good agreement between model and measured data since it falls within the IPCC's ±20% uncertainty limit (IPCC, 2006). Thus, minimum DOC of each waste fraction is more realistic to be used as a site specific value. However, the result is different from Penteado *et al.* (2012) who had a good model fit with an acceptable uncertainty limit for the site specific and maximum DOC values. Different choices of DOC values and different waste composition were identified as the main reason for this contradicting results. According to past studies, a variation in the MSW composition could contribute to high divergence of DOC values due to the fact that different organic material has different degradable rate (Thompson *et al.*, 2009, 2007; Jha *et al.,* 2007; Kim, 2003; Preen & Murphy, 2001).

4.4.2 The influence of DOC_f

The fraction of decomposable organic carbon (DOC_f) is the percentage of DOC that is converted to LFG (IPCC, 2006; Kumar *et. al.*, 2004). The weighted DOC_f values for the bulk waste approach was set at 0.56, 0.77 and 0.91 for minimum, site specific and maximum value, respectively. **Figures 4.4** and **4.5** show the influence of DOC_f on CH_4 generation in the bulk waste approach and waste composition approach, respectively.
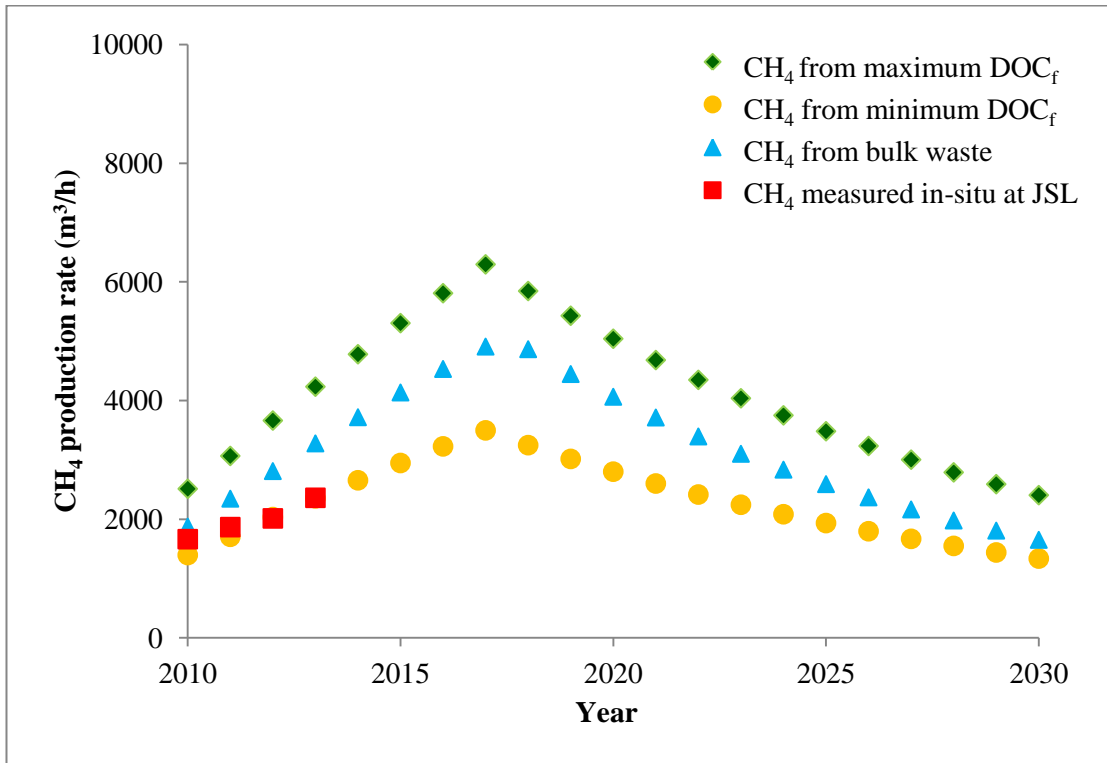
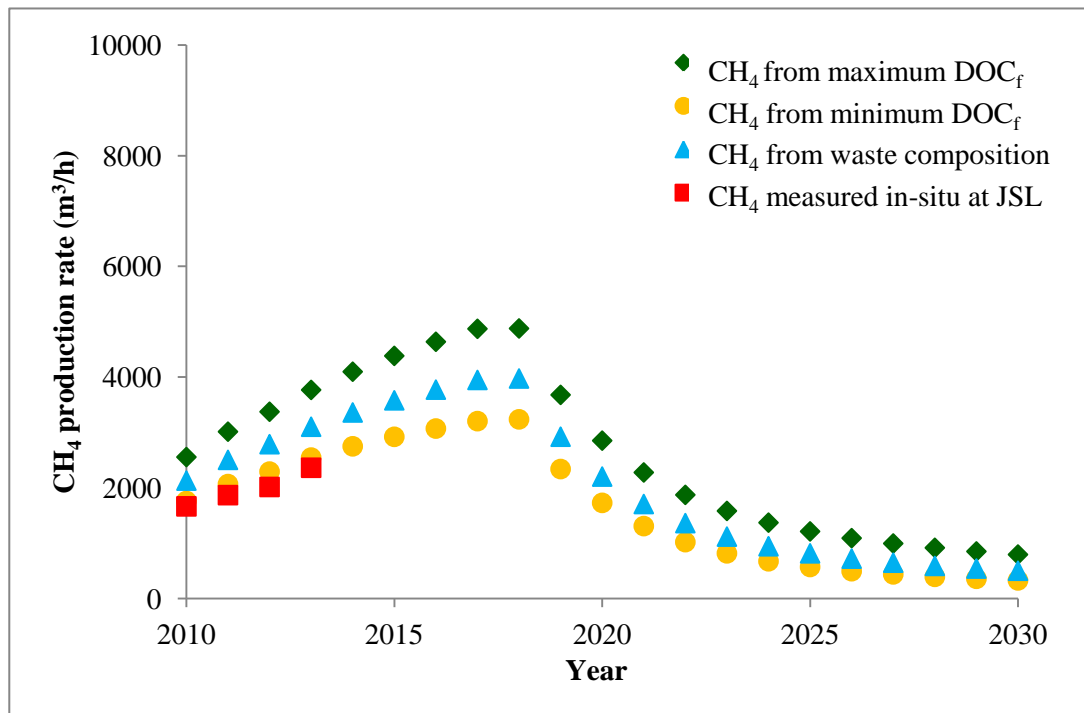**Figure 4.4**: CH_4 generation from DOC_f, using the bulk waste approach

Figure 4.5: CH_4 generation from DOC_f, using the waste composition approach

In **Figure 4.4** the minimum DOC_f value which initially underestimated the CH_4 production in JSL, had the best model fit with the measured CH_4 as compared to the maximum and site specific values. This result is in line with Abushammala *et. al.* (2011) and Weitz *et al.* (2008), who had used DOC_f value of 0.5 in their model projections comparing two different IPCC models, FOD models version of 1996 and 2006. However it is in contradiction with IPCC (2006) and Kumar *et al.* (2004), who had chosen DOC_f value of 0.77 as their default value. In both studies, it was assumed that temperature in the landfill's anaerobic zone remained constant at 35°C. In this case, it can be affirmed that the anaerobic temperature zone in the landfill is not constant at 35°C and could possibly be lower to yield better model estimation for CH_4 produced in JSL. The maximum DOC_f value overestimated CH_4 produced in JSL between 50 to 80%. Hence, the DOC_f value of 0.91 is not a good choice for a maximum value.

Similarly, the minimum value of DOC_f from the waste composition approach (**Figure 4.5**) is presumed consistent with the *in-situ* CH_4 measured at JSL as compared to CH_4 produced in JSL. In other words, it had the least error measured (5 - 15%) compared to site specific (25 − 35%) and maximum DOC_f values (50 − 70%). The variance in the results reflects the fact that different waste fractions degrade at different rate, where some degrades very slowly (Sormunen *et al.*, 2012; Cruz & Barlaz, 2010) while some does not degrade at all in an anaerobic condition (Machado *et al.*, 2009). Hence, LFG generated also varies accordingly. In a study by Thompson *et al.* (2009), it was established that the choice of precise DOC_f values had reduced the error estimates by half for a number of models as well as had a huge impact on the accuracy of estimates. In this study, considering the high percentage of errors (25 − 70%) from both site

specific and maximum DOC_f values, the minimum DOC_f values should be replaced as site specific values for JSL on the basis of waste composition approach.

4.4.3   The influence of decay rate, k

The CH_4 generation rates from different decay rates, k, are shown in **Figures 4.6** and **4.7** for the bulk waste and waste composition approach, respectively. The decay rates for the bulk waste approach were 0.20 y^{-1} (maximum value), 0.15 y^{-1} (minimum value) and 0.09 y^{-1} (site specific value.) In **Figure 4.6**, all three models overestimated CH_4 generation rate at JSL. Thus, this depicts that the IPCC default range (IPCC, 2006) and the modified USEPA formula (USEPA, 2004) in Eq. 6 for decay rate are inaccurate for JSL. These values are too large for JSL although it is a landfill in a tropical country.

In this context, one of the possible reason for lower decay rates could be due to the age of the landfill. In studies by Amini *et al.,* (2012) and Wangyao *et al.,* (2010), the decay rates for tropical landfills below 5 years of operations which were lowered to between 0.08 and 0.20 y^{-1} showed $\pm$ 15% error in measurements between modelled and actual values. JSL is into 7 years of operation since 2007 and active LFG collection was carried out since 2010. Amini *et al.,* (2012) also suggested that delay in installation of LFG collection systems by landfill operators could also attribute to low LFG collection as much CH_4 would have released through the cracks on landfill surface.

While, Barlaz *et al.,* (2009) proofed that for decay rate of $0.08y^{-1}$ almost 30% of the CH_4 generation occurs within 5 years of waste placement. Besides that, Penteado *et al.,* (2012) also points that inadequate extraction of LFG could possibility increase the measurements errors since the measured CH_4 at JSL are always lower than the calculated ones. Therefore, lower range of decay rates similar to those in boreal and temperate climate (Cruz & Barlaz, 2010; IPCC, 2006) and bioreactor landfills (Sormunen *et al.*, 2013; Tolaymet *et al.*, 2010; Machado *et al.*, 2009) were suggested for the site specific values at JSL.

Generally, comparing both **Figures 4.6** and **4.7**, they clearly show that the waste composition approach shows lesser CH_4 production rate as compared to the bulk waste approach which is similar to results obtained by Penteado *et al.,* (2012) and Wangyao *et al.,*(2010). In **Figure 4.7**, the waste composition data was calculated from various decay rates for different composition of waste as shown earlier in **Table 4.2.** The maximum and minimum decay rates were evaluated from the IPCC range for each waste category. The results show that the minimum decay rate underestimated CH_4 generation while the site specific and maximum decay rates overestimated CH_4 production rate. The noticeable difference in the results is because of the waste fractions and various decay rates of the MSW. Amini *et al.,* (2012) in their study concluded that overall degradable material in waste compositions varies annually between 20 to 80%, resulting in the non-uniformed estimation of modelled CH_4 against the actual reading.
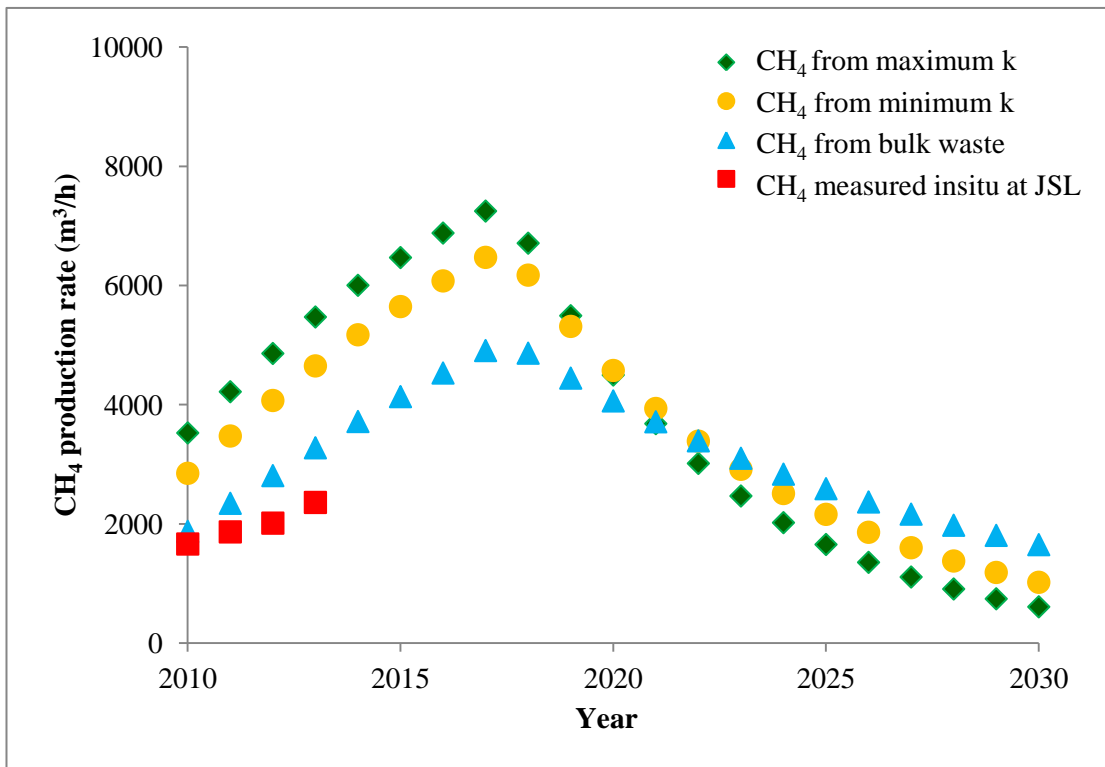
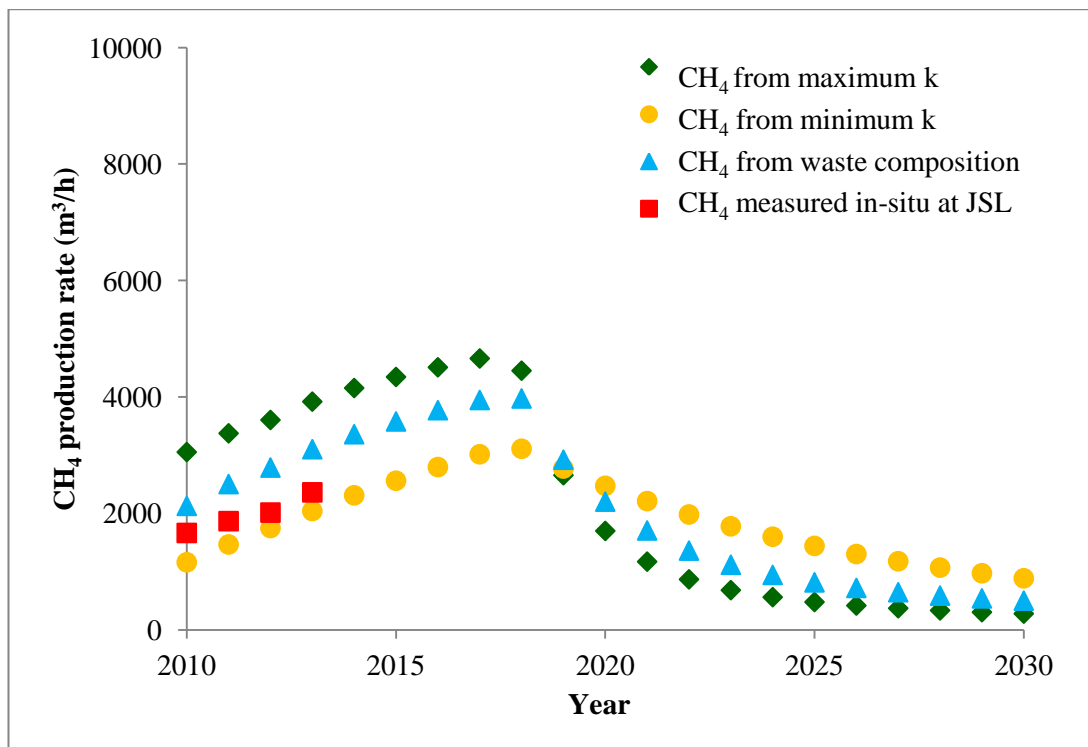**Figure 4.6:** CH_4 generation from different decay rate, k, using the bulk waste approach

Figure 4.7: CH_4 generation from different decay rate, k, using waste composition

4.4.4 Influence of fraction of CH_4 in LFG, F

The fraction of CH_4 present in LFG varies over the year as the rate of degradation of organics in the MSW varies over the years (Amini *et al.*, 2012; IPCC, 2006). In most cases the default rate for this value will be at 0.5 accounting for 50% of the LFG to be CH_4 as supported by many studies (Perteado *et al.*, 2012; Wangyao *et al.*, 2010; Weitz *et al.*, 2008; Kumar *et al.*, 2004; Tchobanoglous *et al.*, 1993). In this study the chosen F values were 0.5, 0.6 and 0.7 representing the minimum, site-specific and maximum F values for both approaches. These values were chosen based on the default value, current composition and future projection of the CH_4 at JSL.

Figure 4.8 exhibits the projection rate of CH_4 using the bulk waste approach. From the figure it is evident that the default value of 0.5 fraction of the CH_4 in LFG is more in agreement with CH_4 measured at JSL. This shows that the IPCC (2006) estimation of F = 0.5 is preferred even if the actual CH_4 value in the LFG measured is higher. The difference in percentage between the estimated amount and actual amount of CH_4 generated for the F parameter is explained in detail in the error function analysis section.

In **Figure 4.9**, the CH_4 generation using waste composition approach is highlighted. Similar results as bulk waste approach were obtained. The IPCC default value of F=0.5 was the best fitting to the measured data while the other two values overestimated the amount of CH_4 generation. This is suggestive that the amount of CH_4 in LFG which is above 50% of the total concentration is not represented correctly in the calculation.
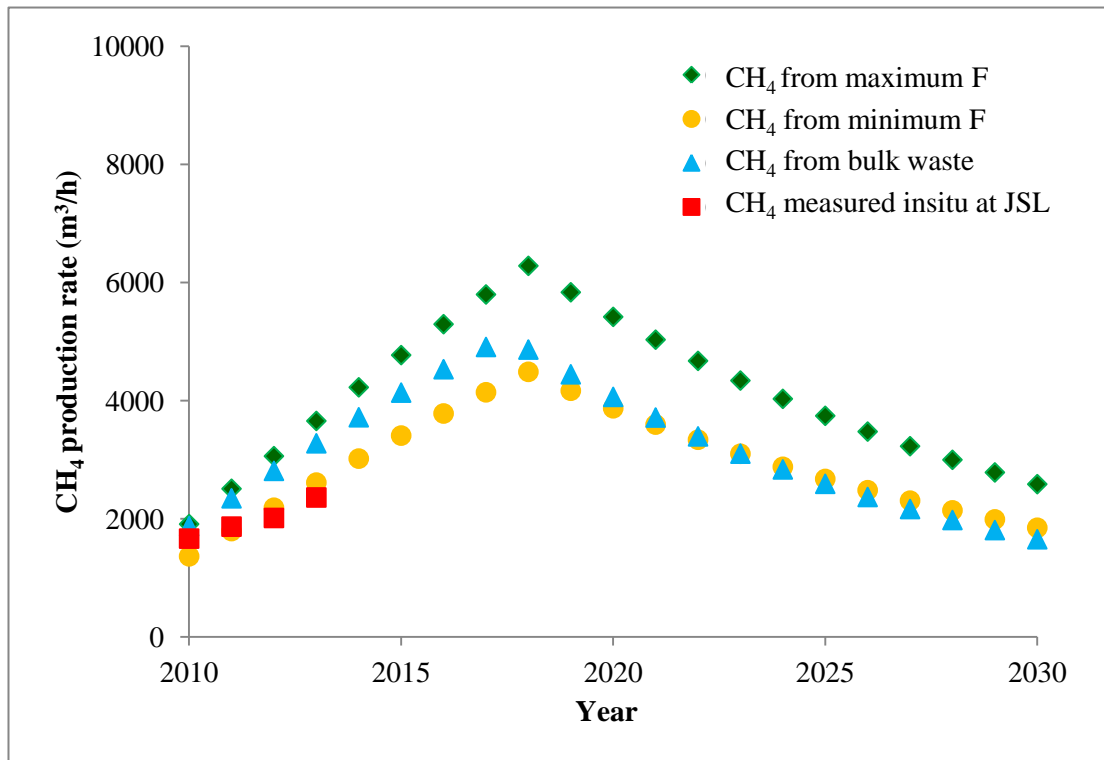
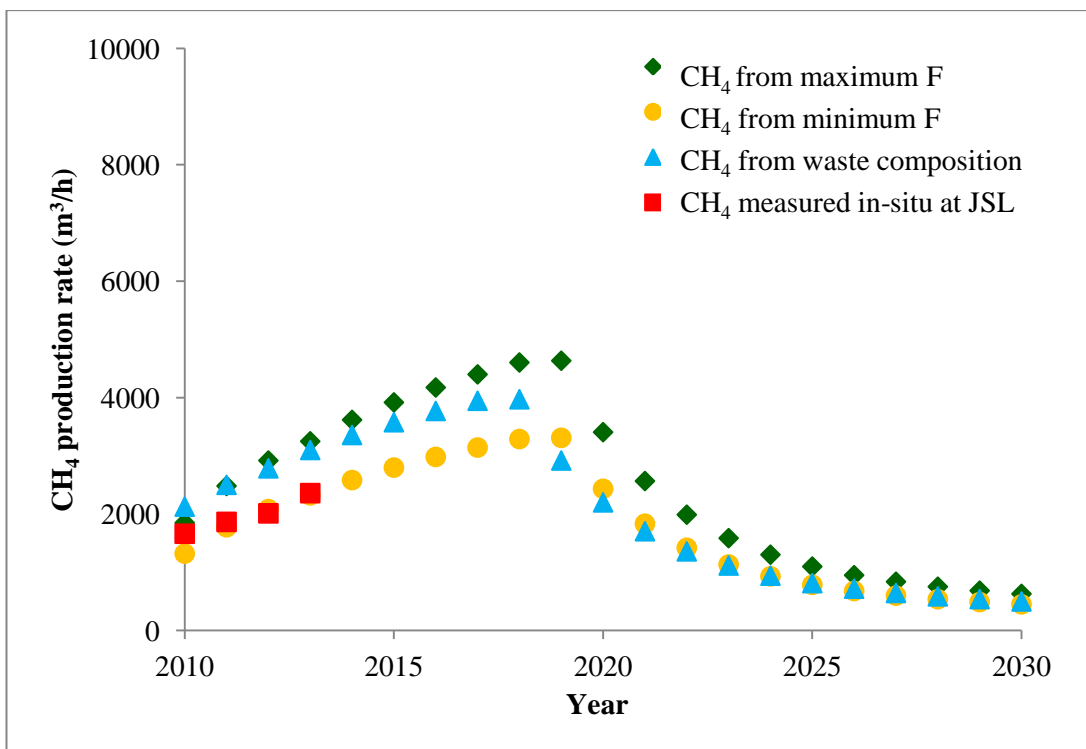**Figure 4.8:** CH_4 generation from different CH_4 fraction in LFG, using the bulk waste approach

Figure 4.9: CH_4 generation from different CH_4 fraction in LFG, using waste composition

4.4.5 Influence of Methane Correction Factor, MCF

Methane correction factor refers to the condition of the landfills. In general a well-managed and engineered landfill produces more CH_4 as compared to the unmanaged landfill sites or dumpsites. According to Wangyao *et al.,* (2010) who had used the IPCC Waste Model for landfill CH_4 estimation in Thailand, attributed that the possible intrusion of air into the landfills in unmanaged sites could decrease the anaerobic waste degradation. Hence, reducing the production of CH_4 at these sites. This conclusion was related to a study by Peck *et al.*, (2007), who recognized the reduction of landfill CH_4 emission when the waste was stabilized rapidly through aerobic conditions.

Therefore, in this study the MCF values were selected based on the different conditions within JSL which had waste between one to seven years. The values were 0.5, 0.6 and 0.8 for minimum, site-specific and maximum values for both approaches. Referring back to Chapter 3 Section 3.1.2.4 these values of MCF were assigned to different type of landfill sites. However, in this study MCF of 0.5 represents area with waste between 1 to 2 years, 0.6 represents waste between 3 to 5 years and 0.8 refers to waste aged more than 5 years. Although MCF refers to the type of landfill, in this study it is compared to the age of the landfill which approximately identify the depth of the landfill area. It was assumed that the more aged, the deeper the area of landfilling. The following **Figures, 4.10** and **4.11** show CH_4 generated using the three values for both bulk waste and waste comparison approaches.
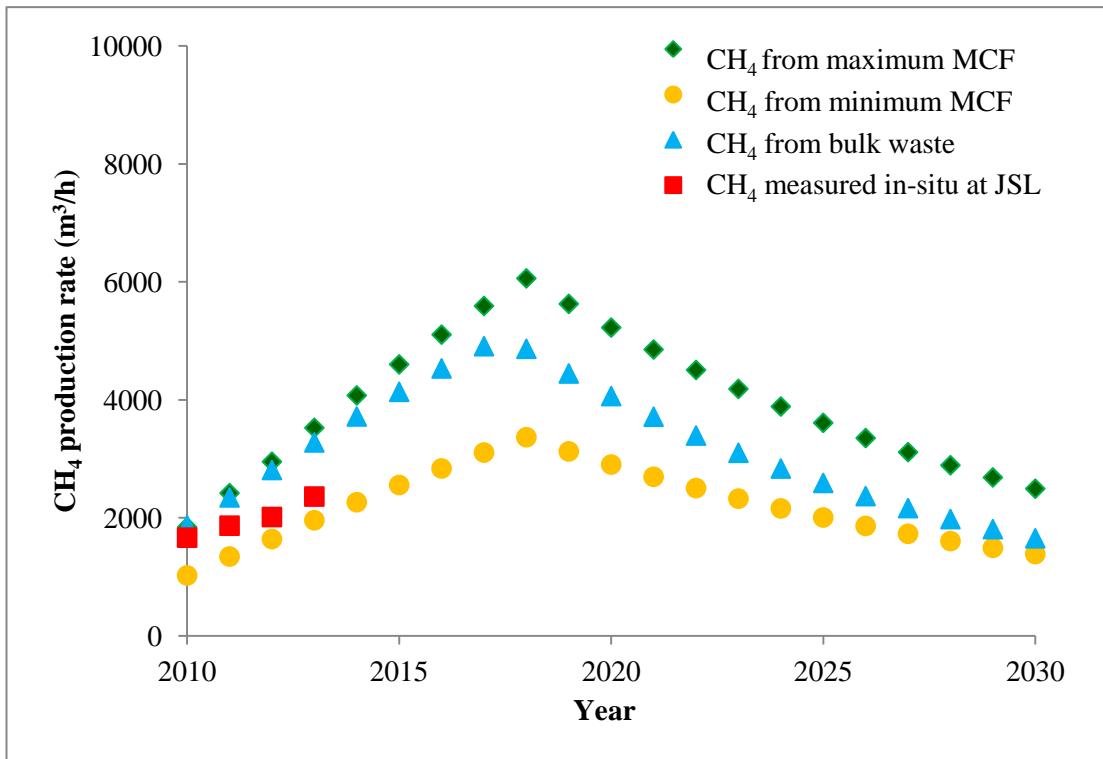
Figure 4.10: CH$_4$ generation from different values of Methane Correction Factor, using the bulk waste approach
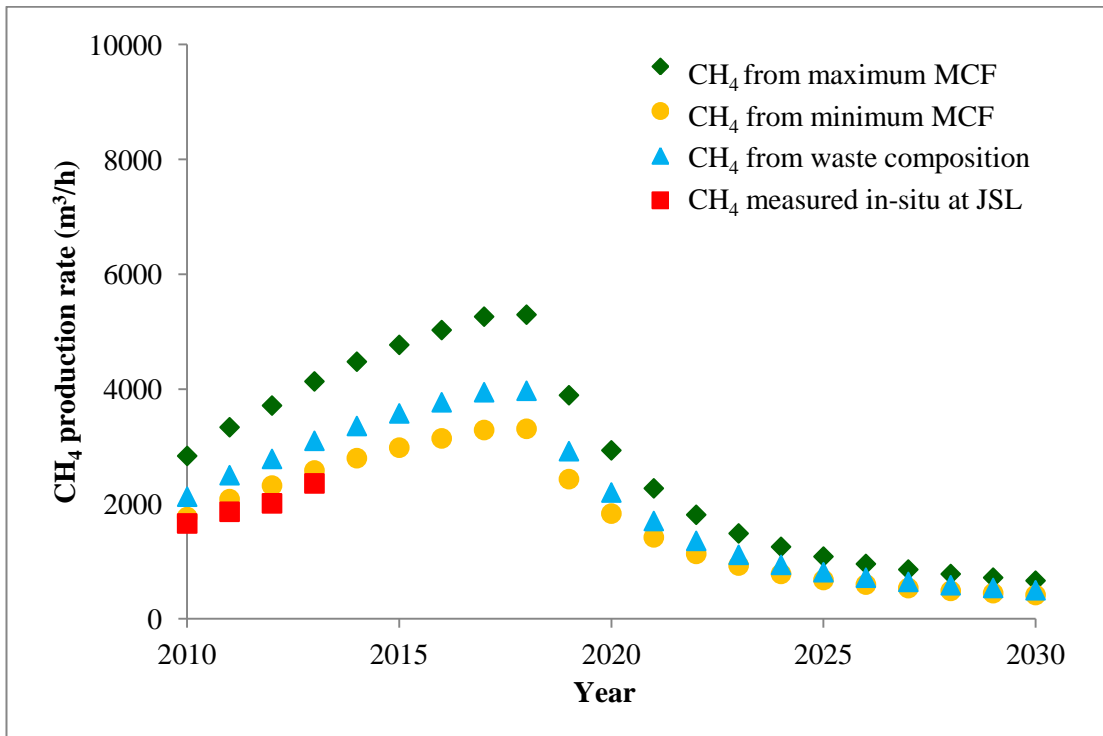

Figure 4.11: CH$_4$ generation from different values of Methane Correction Factor, using the waste composition approach

From **Figure 4.10** it is apparent that the site-specific value and maximum value of MCF overestimated the amount of CH_4 that can be generated in JSL. However, the minimum value of MCF used under-predicted CH_4 generation suggested that the value chosen was too low for calculation. As for the waste composition approach, all three values had overestimated the amount of CH_4 generated (**Figure 4.11**). Therefore, this shows that the MCF given by IPCC for different categories of landfills and dumpsites are not applicable to all countries. Similar results were also observed by Wangyao *et al.*, (2007) who reviewed landfills and dumpsites in Thailand and used much lower MCF values as compared to the default IPCC data. The MCF values there were corrected to 0.65, 0.20, 0.15 and 0.1, to represent, deep landfills, shallow landfills, deep dumpsites and shallow dumpsites.

4.5 Error Function Analysis

The Error Function Analysis (EFA) used to improve the accuracy of model prediction showed the best fitting for each parameter with the lowest error function value. The analyses were done using different measure such as the fractional bias (FB), root mean square (RMSE) and the normalized root mean square error (NRMSE) as used by many researchers and modelers for model validation exercise (Cervone & Franzese, 2010; Allen *et al*., 2007; Haupt *et al.*, 2006; Chang *et al.*, 2003; Hanna *et al.*, 1993). Each measure reflects the spatial distribution of the mean value, and the appropriate use of one measure depends largely on the characteristics of the concentration field (Cervone & Franzese, 2010). **Table 4.6** shows the results of error function analysis performed for each of the parameters used in this study. FB mainly measures the over- and

underprediction of the calculated data with respect to the measured data. RMSE and NRMSE are reflected on the systematic bias and relative random errors differing in the normalization over the average (Cervone & Franzese, 2010).

Table 4.6: Percentage of error from different measures of error analyses. **Red** indicates error above sixty percent and **blue** indicates error below ten percent.

Parameter	Bulk Waste			Waste Composition		
	FB	NRMSE	RMSE	FB	NRMSE	RMSE
SITE_SPECIFIC	37.3%	40.1%	48.4%	36.0%	50.0%	44.5%
Maximum DOC	**89.2%**	**102.7%**	**165.9%**	59.0%	**76.8%**	**84.4%**
Minimum DOC	11.2%	14.8%	15.7%	20.6%	45.4%	18.9%
Maximum DOC_f	52.1%	56.1%	**73.3%**	56.9%	**75.4%**	**80.6%**
Minimum DOC_f	**5.4%**	**8.2%**	**7.9%**	32.0%	56.6%	38.8%
Maximum k	**78.3%**	**86.6%**	**131.0%**	51.2%	**71.6%**	**69.1%**
Minimum k	**62.3%**	**67.3%**	**92.9%**	**1.7%**	13.2%	6.7%
Maximum F	52.0%	56.0%	**73.0%**	55.7%	**74.6%**	**78.3%**
Minimum F	19.5%	21.9%	24.1%	23.5%	48.4%	27.3%
Maximum MCF	48.6%	52.2%	**66.8%**	**60.6%**	**77.9%**	**88.1%**
Minimum MCF	**9.2%**	10.8%	10.3%	15.5%	39.4%	17.5%

From the **Table 4.6**, it can be concluded that the NRMSE and RMSE showed higher percentage of error as compared to the FB measure. This is because a minimum threshold for the model estimate was not set within the NRMSE and RMSE measure (USEPA, 2004). While FB on the other hand, is a more useful model performance indicator because it has an advantage of weighing negative and positive bias estimate. In general, perfect model estimation should have FB, NRMSE and RMSE of 0.0%.

Further deduced from **Table 4.6**, the site-specific values used for both the approaches showed error estimation between 36 to 60% which indicates that the accuracy of the model estimated data is only between 40 to 64% . Thus, this provides room for further improvement on the site-specific values. The highest percentage of error was 165% obtained from the maximum DOC and the lowest was 1.7% from the minimum k value. For the purpose of this study, any error estimate over 60% was considered as poor performance of the model and is indicated in red in **Table 4.6**. Whereas, the blue indicates good model performance with error estimate of less than 10.

Therefore each parameter which showed error estimate more than 60% was revaluated and new figures were assigned to it with errors below $(30 \pm 20)\%$ to obtain a good model performance. From this exercise a new set of site specific as well as minimum and maximum ranges of each parameter was set for JSL. Future CH_4 generation at JSL using the IPCC Waste Model can be calculated using these figures without using the IPCC default data. **Table 4.7** shows the new parameter sets to be used for calculation of CH_4 at JSL.

Table 4.7: New set of parameters proposed for JSL with reduced error

No.	Parameters			Site-Specific	Minimum	Maximum
1.	Degradable Organic Carbon (DOC)	BW		0.13	0.12	0.15
		WC	FW	0.15	0.10	0.20
			PT	0.30	0.20	0.35
			WS	0.40	0.39	0.43
2.	Fraction of DOC decomposed (DOC_f)	BW		0.56	0.50	0.70
		WC	FW	0.50	0.45	0.58
			PT	0.30	0.25	0.40
			WS	0.17	0.10	0.33
3.	Decay rate (k) , year^{-1}	BW		0.09	0.08	0.12
		WC	FW	0.30	0.14	0.35
			PT	0.07	0.06	0.08
			WS	0.04	0.03	0.05
4.	Fraction of CH_4 in LFG (F)	BW & WC		0.55	0.50	0.60
5.	Methane Correction Factor (MCF)	BW & WC		0.6	0.55	0.65

BW – Bulk Waste; WC – Waste Composition; FW – Food Waste; PT – Paper&Textile; WS –Wood&Straw

4.6 Flux Measurements of CH_4

The flux measurement of CH_4 denotes to the surface emission of CH_4 in the landfill. Surface emission of CH_4 in landfills emerges from a complex interaction of biological, chemical and physical processes within the landfill cover with different spatial and temporal scales (Spokas *et al.*, 2003). The flux measurement of CH_4 was calculated at each grid point using the static flux chamber technique. This technique is a common practice for surface measurements at landfills and frequently measured in the range of grams CH_4 per square meter per day (Abichou *et al.*, 2006; Bogner *et al.*, 2005; Chanton & Liptay, 2000; Borjesson & Svensson, 1997; Czepial *et al.*, 1996; Bogner & Spokas, 1993). From literature it is evident that surface flux at landfills have high spatial variability (Spokas *et al.*, 2003; Börjesson *et al.*, 2000) and have been reported to vary over seven orders of magnitude from 0.0004 to 4000 $gm^{-2}day^{-1}$ (Bogner *et al.*, 1997).

In this study, CH_4 flux measurements were taken during two seasons; the dry period (May to July) and rainy period (October to December), correlating with the dry and wet period at JSL as shown in **Figure 4.12.** As JSL is situated in the west coast of Peninsular Malaysia, it has a prominent rainy period during the month of October to December coinciding with the Northeast Monsoon season over Malaysia (MetMalaysia, 2013). Also notable is the drier season during the month of June to August (MetMalaysia, 2013) with slight variation at certain places. The different in emission rate and the influence of the meteorological parameters were also evaluated. The error bars shows the standard errors of the data set.
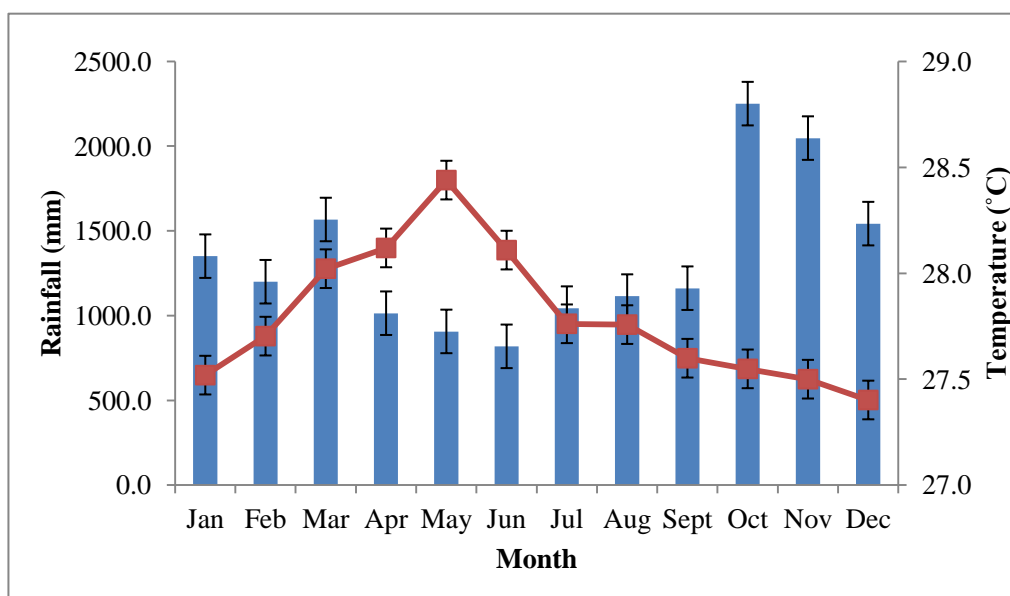
Figure 4.12: Average rainfall and temperature reading for JSL from 2001 to 2013

A total of 120 CH_4 flux measurements were taken during the time of study at grid points over a closed cell in JSL. This cell was actively used between 2008 and 2009 before being closed partially in 2010. The total amount of MSW received at this cell was 366,000 tonnes. The cell is temporarily covered using clay liner and many cracks are visible on the surface of the cell. In all, 95% of the flux measurements had fulfilled the correlation coefficient, $R^2 > 0.7$ for dC/dt which is an important indicator of data quality and acceptance criterion for flux measurement (Fourie & Morris, 2004; Bogner *et. al.*, 1997). dC/dt is the concentration gradient (a constant) when the CH_4 concentration is plotted against time.

The frequency distributions of total CH_4 during both the wet and dry period were plotted out in **Figure 4.13** and **Figure 4.14**. The flux readings ranged between 0 to 4000 and 0 to 2000 $gm^{-2}day^{-1}$ for the wet and dry period, respectively.
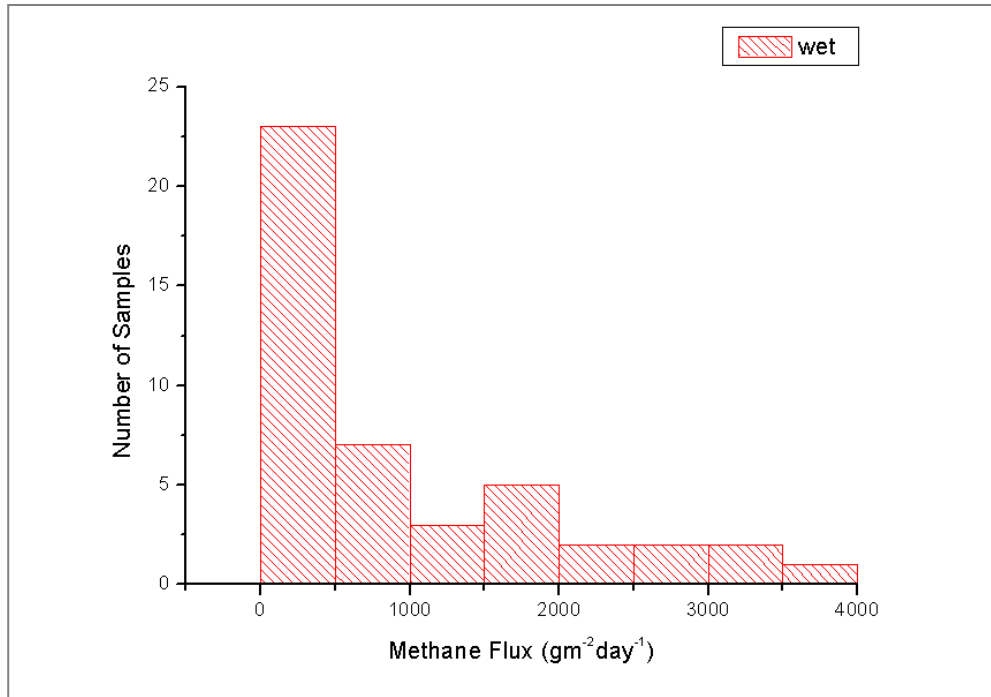
Figure 4.13: Histogram for flux measurement during the wet period of October to December 2012
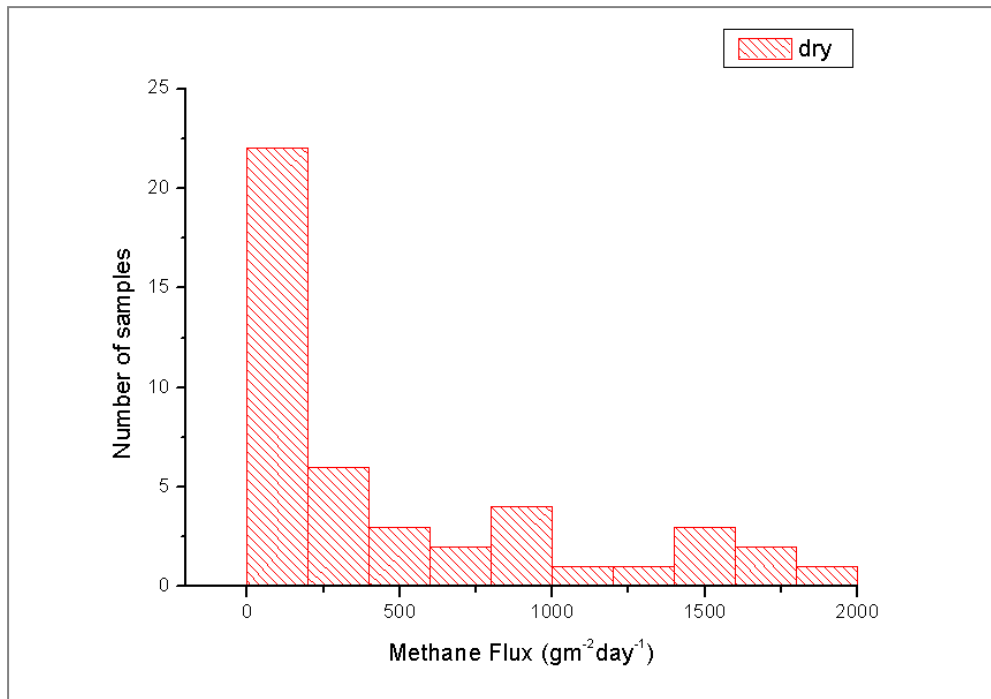

Figure 4.14: Histogram for flux measurement during the dry period of May to July 2013

Both the histograms are highly skewed and not normally distributed. **Figure 4.13** shows the histogram for the wet period with an arithmetic mean flux of 885 g m^{-2} day^{-1}. However, this mean is not considered to be a good representative of the flux emission due to the skewness of the data distribution which is sensitive to extreme values (McDonald, 2009). Furthermore in a study by Spokas *et al.,* (2003), it was well attributed that the use of arithmetic mean could over- or underestimates the surface emission of CH_4 since all the measurements are equally weighed regardless of the extreme values. Therefore it is normally replaced with the geometric mean and in this case the geometric mean was 590 g m^{-2} day^{-1}. The geometric mean is 33% lower than the arithmetic mean, consistent with results obtained by Abushammala *et al.*, (2012). The transformation of arithmetic mean to geometric mean is normally done using the log normal transformation (McDonald, 2009; Abichou *et. al.*, 2006).

While in **Figure 4.14,** the histogram for flux measurement during the dry period, shows the arithmetic mean was attributed at 536 g m^{-2} day^{-1} and the geometric mean was at 383 g m^{-2} day^{-1}. This result is in agreement with those of Abushammala *et. al.* (2012) and Abichou *et. al.* (2006) that the arithmetic mean is higher compared to the geometric mean. In this case it is almost 1.5 times more. From both the histograms it is apparent that a big variability exists in the flux measurements. This is due to the fact that the surface emission at different location along the grid points were subjected to landfill topography, cover thickness, CH_4 oxidation activity, underlying waste composition and hotspots with active gas migration (Abushammala *et. al.*, 2012; Chakraborthy *et. al.*, 2011; Abichou *et. al.*, 2006, Spokas *et. al.*,2003).

4.7   Surface plots of CH$_4$

The surface plots of CH$_4$ flux from landfills were not spatially uniform. During measurement period, hot spots with visible gas bubbles during the wet condition were seen around the study area. This was because during the rainy period, the gas migration at the landfill cover is governed by bubbling (Abichou *et al.*, 2006). When the water becomes stagnant at certain flat areas, the landfill cover loses its shear strength and become vulnerable for gas diffusion. Thus, the bubbles are seen at these spots. Keeping this in mind, taking the average flux measurements may not accurately represent flux of the area. For the purpose of accounting spatial variability, the Inverse Distance Weighting (IDW) and Kriging were used as interpolation method (Abushamala *et al.*, 2012; Abichou *et al.*, 2006; Fourie & Morris, 2004, Spokas *et al.*, 2003).

From previous literature it has been agreed that there are many method used to estimate the mean surface emissions from landfills such as arithmetic, geometric, geospatial and tributary area means (Abichou *et al.*, 2006; Ishigaki *et al.*, 2005; Fourie & Morris, 2004; Spokas *et al.*, 2003). Thus, both the IDW and Kriging methods produced geospatial mean which is considered the most precise figure and has been commonly used to estimate total LFG emission from landfills (Abushammala *et al.*, 2012; Fourie & Morris, 2004). In the Kriging method, the flux reading of an unknown location is interpolated with the semivariograms in which the variance between sampled points decreases as separation distance decreases. While in the IDW method, the interpolation is calculated by weighing the neighboring value using the inverse of the separation distance to a power (Abushamala *et al.*, 2012; Abichou *et al.*, 2006). Both the interpolations were later converted into contour maps.

4.7.1 Surface plot for the wet period

Figures 4.15 and **4.16** shows the surface contour maps of CH_4 emission for JSL during wet period using both Kriging and IDW methods, respectively. The contour intervals chosen for the analysis were at an increase of 200 g of CH_4 m^{-2} day^{-1}. From both maps, it is evident that higher the elevation the higher is the concentration of CH_4 fluxes. Point I is the peak of the landfill area with a height of 4 meters and it is estimated to have most of the MSW embedded within it. There were a lot of visible bubbles at point I during the wet period. There was also a strong smell of CH_4 detected during the field measurement period during both seasons. In the lower periphery (D, H, L and P) it is noticeable that the CH_4 flux is almost nearing to zero. Point B on the surface map, is the location of the flare unit in JSL.

At a glance, the contour maps of CH_4 emissions during wet period produced by Kriging and IDW methods showed similar trend. However, the Kriging method produced had a narrower range of values and natural looking contours then the IDW method, similar to that observed by Abushammala *et al.*, (2012), Abichou *et al.*, (2006) and Spokas *et al.*,(2003). One set back observed in Kriged contours were the poor prediction of the highest peaks and valleys of the data which is more prominent in the IDW contours (Spokas *et al.*, 2003).
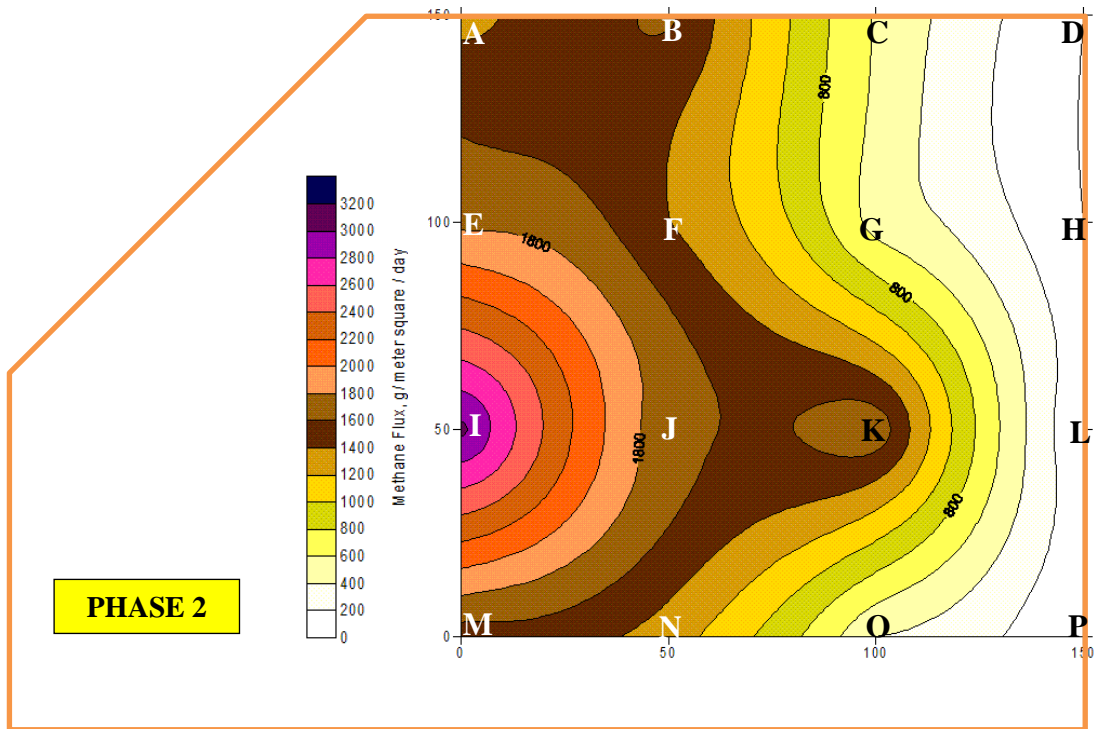
Figure 4.15: Contour map of flux measurement during the wet period (Oct to Dec 2012) using the Kriging method overlaid on the Phase 2 cell at JSL
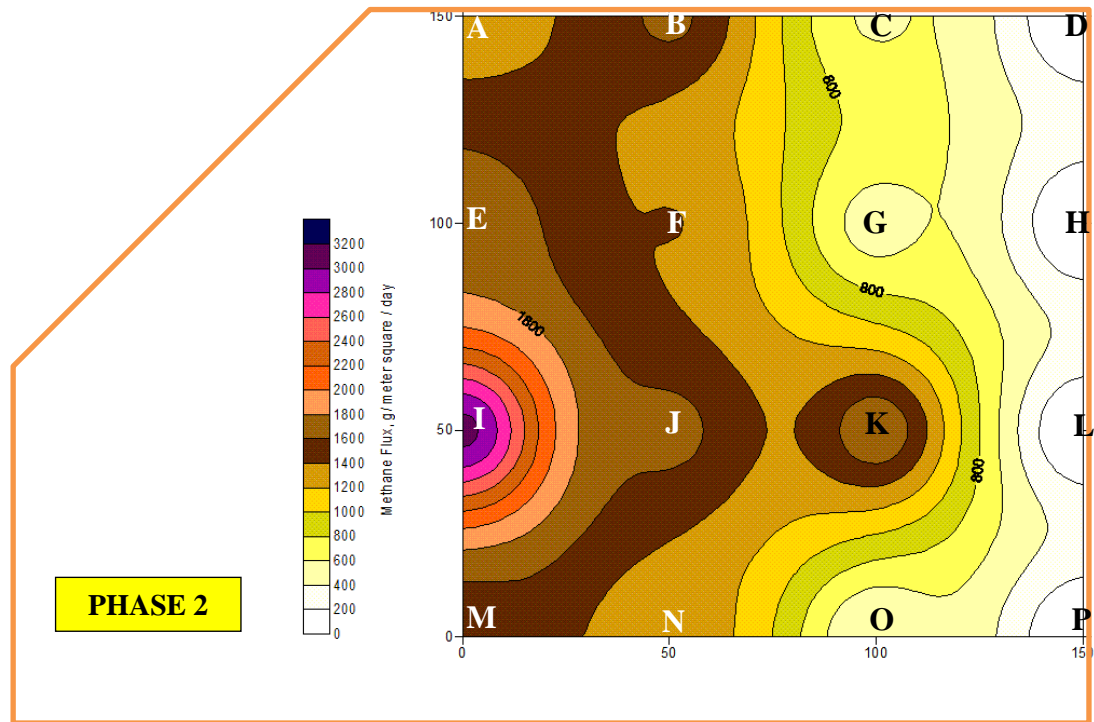

Figure 4.16: Contour map of flux measurement during the wet period (Oct to Dec 2012) using the IDW method overlaid on the Phase 2 cell at JSL

4.7.2 Surface plot for the dry period

Figure 4.17 shows the contour map for the dry period using the Kriging method. Similar to the wet season the high concentration of flux was observed at grid point I which is the peak of the landfill site. Also in point B where the flare unit is located, high concentration of methane flux was noticed. **Figure 4.18** is the contour map of dry period using the IDW method. Both the Kriging and IDW methods also showed similar emission trends for the dry period. The only difference is the IDW method has more defined peaks and valleys as compared to the Kriging method.

Comparatively, the concentration of CH_4 surface emission was lower in the dry period as compared to that of the wet period. Similar results were achieved by Wangyao *et al.* (2010) who had worked on landfill gas emission in Thailand and Abushamala *et al.* (2012a, 2012b) who had calculated CH_4 fluxes from Sungai Sedu Open Dump in Malaysia. From this observation two conclusions could be made regarding the difference in surface emission between the two periods; (1) During the wet period, water saturates the landfill cover inhibiting CH_4 surface emission. Thus, poor shear strength of the top soil caused CH_4 to be released in abundance at hot spots on the surface (Spokas *et al.*, 2003); (2) Higher level of CH_4 oxidation during the dry period due to higher temperature level could elevate the CH_4 emission out of the landfill cover layer, thus creating a low concentration of CH_4 on the surface (Fourie & Morris, 2004).
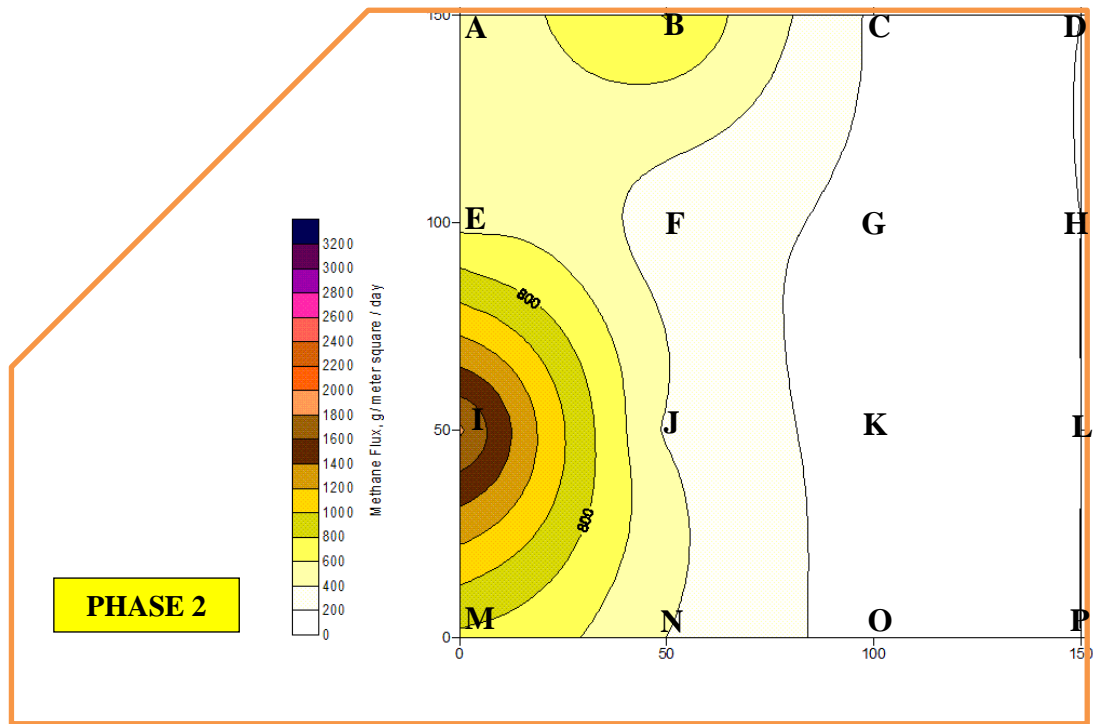
Figure 4.17: Contour map of flux measurement during the dry period (May to July) using the Kriging method overlaid on the Phase 2 cell at JSL
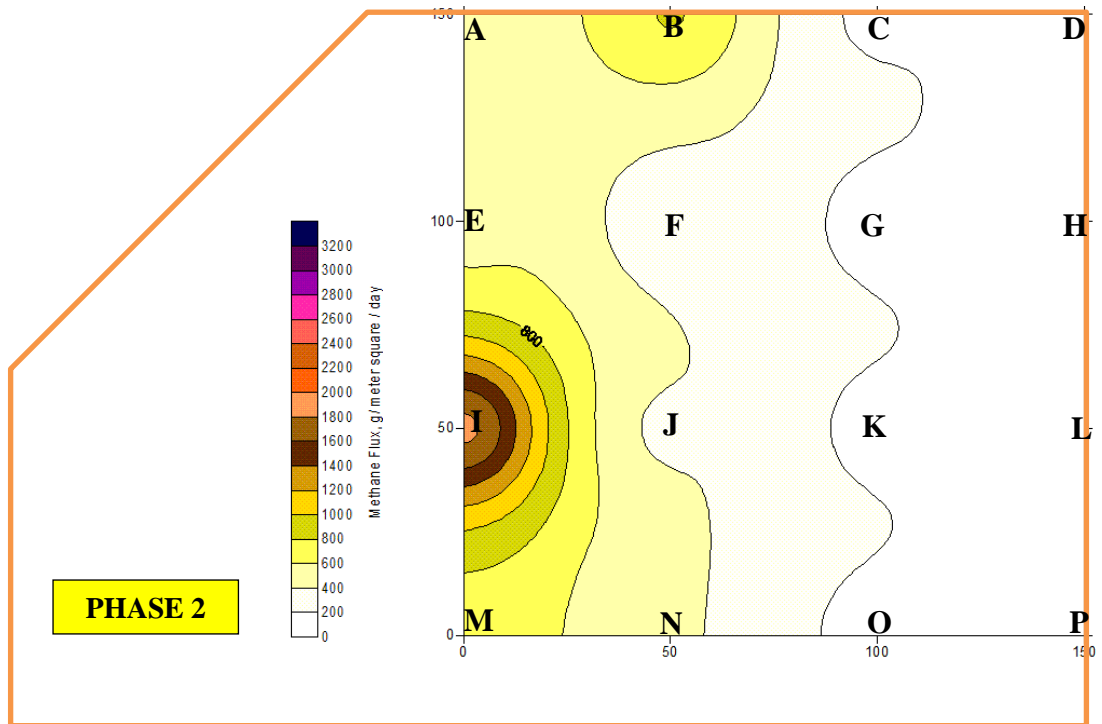

Figure 4.18: Contour map of flux measurement during the dry period (May to July) using the IDW method overlaid on the Phase 2 cell at JSL

According to Cardellini *et al.* (2003), to achieve a reliable set of surface emission data numerous measurement with a subsequent treatment to the measured data is thoroughly needed. Therefore in this study, the statistical analysis for the geospatial mean, cross-validation residual mean squares and model residual mean squares was derived using Kriging and IDW method for CH_4 flux (Fourie & Morris, 2004). The cross-validation residual was performed by removing the measured flux data from the data set and using the remaining data set and the model to predict the removed value. The difference between the measured and predicted flux values is the cross-validation residual. The comparison between two methods showed that the IDW method yield a smaller degree of error than the Kriging method. This is in agreement with results obtained by Abushmmala *et al.* (2012a, 2012b); Abichou *et al.* (2006) and Spokas *et al.* (2003). Therefore, CH_4 flux mean was estimated using the geospatial mean via the IDW method.

Table 4.8 depicts the mean and standard deviation calculated using the arithmetic, geometric and geospatial scales. Coefficient of variance (CV) values were also used for comparing the different means and standard deviation. In general the arithmetic and geospatial mean have almost similar means because both used the minimum and maximum flux value for calculation and interpolation (Abichou *et al.*, 2006; Spokas *et al.*, 2003). The geometric mean doesn't take into consideration the extreme values. Also, looking from the standard deviation figures, the arithmetic scale is the highest among all due to the fact that the arithmetic calculation takes into account the outliers of the flux data.

Table 4.8: Descriptive statistics of CH$_4$ flux emission (g m^{-2} day^{-1})

Properties	Wet period	Dry Period
Minimum	0	0
Maximum	3059	1840
Arithmetic Mean	885	536
Arithmetic Standard Deviation	1052	664
Arithmetic C.V (%)	**119**	**123**
Geometric mean	590	383
Geometric standard deviation	569	345
Geometric C.V (%)	**96**	**90**
Geospatial Mean (IDW)	989	381
Geospatial Standard deviation	850	354
Geospatial C.V (%)	**86**	**93**

On the other hand, the CV is also a good comparison method as it represents the percentage of ratio between the standard deviation and mean (Fourie & Morris, 2004). Therefore, it can be used as an inter-comparison between the different scales. From previous literatures, the CV value varied between 23 to 506% and was projected to give

accurate estimate of measured LFG emission (Fourie & Morris, 2004; Borjesson *et al.*, 2000; Boeckx *et al.,* 1996; Czepiel *et al.*, 1996).   The lower CV indicates lower variation. Among the three different types of mean and standard deviation compared, geospatial scale has the lowest CV value. Thus, in this study the geospatial mean and standard deviation will be used as an estimate for surface emission of CH_4 from JSL.

4.8   Calculation of CH_4 generation at the partially closed cell

The IPCC Waste Model with the corrected parameters from **Table 4.1**, was used to calculate CH_4 generated at the partially closed cell (Phase 2) where the grid points and surface flux measurement were taken. The amount of waste deposited into this cell was used as a reference for calculating the amount of CH_4 generated. From the model, it was calculated that an average of 1826 g m^{-2} day^{-1} of CH_4 will be generated and emitted at the cell during the time of measurement. The emission rate was calculated, in view of the age of the refuse, temporary clay cover and gas extraction wells. But it was just subjected to the bulk waste approach as the record of waste fraction which entered the cell was unavailable. Similar method of calculation was adapted by Abushammala *et al.,* (2012b) in comparing the surface emissions of CH_4 with the IPCC Waste Model generated value at Sungai Sedu Open Dumpsite.

4.9   Cross verification of surface emission and model calculation

The mean flux of CH_4 from the geospatial mean was 989 g m^{-2} day^{-1} while the model estimated an average of 1826 g m^{-2} day^{-1}, almost twice the flux estimate. The difference

in the figure could be due to the fact that the model had overestimated the CH_4 generation and because of the mass balance of CH_4 within the landfill. From the mass balance equation stated in previous Section 2.11, the amount of CH_4 generated in a landfill will be subjected to recovery, surface emission, lateral migration and oxidation (Chanton *et al.*, 1999; Liptay *et al.*, 1998; Bogner *et al.* 1997; Bogner & Spokas, 1993). Otherwise, it could also be an estimated model. Penteado *et al.*, (2012) had insisted that waste composition analysis is definitely needed before calculating CH_4 generation from the model. Hence, the absence of such data from the partially closed cell could have overestimated the modelled CH_4 generation.

In JSL the recovered LFG is normally flared as it is not enough for LFG recovery for energy utilization. It was also noticed during the field measurement period that the flare unit often malfunctioned and was not in use. Therefore, it was most likely that the LFG generated was collected within underground gas wells and stored. The increased pressure from LFG production was probably the main reason the gas begun to ooze out through lateral migration. During wet period visible bubbles (**Plate 4.1**) were evident of lateral migration of LFG while during dry period the visible cracks (**Plate 4.2**) on the landfill surface were the main source of emission.

Plate 4.1: Visible bubbles from the surface of JSL during wet period

Plate 4.2: Visible cracks on JSL cover soil during dry period

4.10 Influence of meteorological parameters on CH$_4$ emission

In this study, the effects of meteorological parameters on the surface emission of CH$_4$ were also evaluated. Among the meteorological parameters that were studied were rainfall, temperature, humidity and atmospheric pressure. From literature it was evident that many researchers have studied the importance of meteorological parameters on surface emission of CH$_4$ (Wang *et al.*, 2012; Christophersen *et al.*, 2003; Czepiel *et al.*, 2003; Galle *et al.*, 2001). However, very few have attempted the study in a tropical climate. Tropical climates are considered to be the wettest climate with occasional dry spells. Climate is considered as one of the important factor that controls the thermal regime of landfills (Hanson *et al.*, 2008).

The rainfall data for this study was obtained from the Bukit Kerayong Oil Palm Estate which is within 5km radius of JSL. Rainfall is considered as a significant parameter to the surface emission because rainwater influences the waste degradation. It also helps to stimulate the microbial activity within the cover soil. Generally the biodegradation of the organic waste fraction is higher in the sanitary landfill than in open dumpsite (Wangyao *et al.*, 2010). This is because in a sanitary landfill the cover layer provides favorable conditions for methane production (Chiemchaisri *et al.*, 2007; IPCC, 2006).

In previous studies by Marion *et al.*, (2001) and Suwansawat (1997), the atmospheric humidity and temperature were correlated with the surface emission of the landfills. For these purpose, soil samples from the soil top cover were collected and analyzed in the

laboratory. But this method was considered ineffective as during sample collection the site requires removal of the cover system which causes disturbance to the soil condition. Other initiative to measure humidity was to use the time domain reflectometer (TDR) which is a very delicate and expensive machine (Tecle *et al.*, 2009). For the purpose of this study the atmospheric humidity was measured using the wet bulb and dry bulb thermometer which was placed in the landfill site during field measurement. These instruments measure both the ambient temperature and atmospheric humidity.

The response to atmospheric pressure of the surface emission of CH_4 was examined by Czepiel *et al.*, (2003). The significant relationship between the emissions and surface atmospheric pressure was obtained. In this study, the atmospheric pressure were obtained using barometer which was placed in the landfill site during the field measurements. In addition for continuous data, the hourly atmospheric pressure data from the Mardi Meteorological Auxiliary Station was averaged. The meteorological station is located approximately 8km away from JSL. During measurement period, no sudden changes were observed in the atmospheric pressure as Malaysia, a country in the Equator, is not influenced by any large pressure systems (MetMalaysia, 2013).

4.11   The meteorological observation and results

4.11.1 The rainfall pattern at JSL

The rainfall pattern in JSL showed an interannual variability. **Figure 4.19** shows the annual rainfall pattern for JSL from 2003 to 2012. Year 2011 was the wettest year as it

recorded accumulated rainfall of 1800mm. Year 2007 and 2009 also recorded above 1500 mm of accumulated rainfall, whereas 2006, 2008, 2010 and 2012 recorded below 1500 mm rainfall. As for the monthly rainfall pattern, more rain were received in October to December and drier weather were recorded from May to July. The rainfall pattern for JSL is similar to rainfall pattern for Western Peninsular Malaysia (MetMalaysia, 2013).
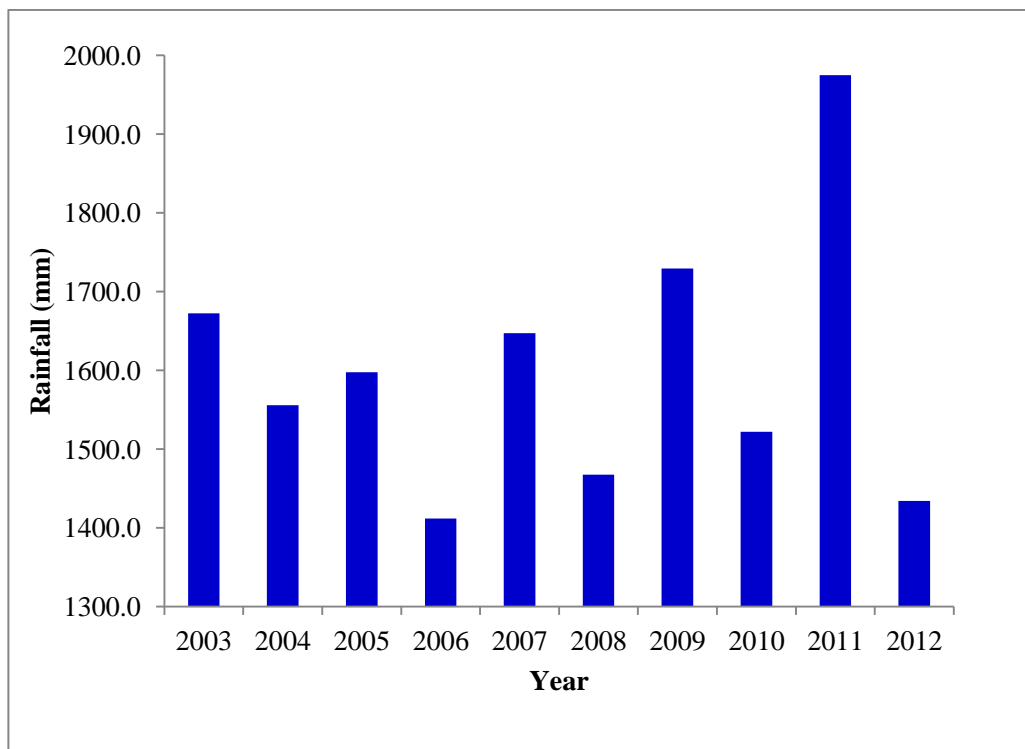

Figure 4.19: Annual rainfall at JSL from 2003 to 2012

4.11.2 Temperature pattern at JSL

The daily temperature at JSL does not have a significant difference all year around because of its tropical climate.   But, the pattern is different between day and night with highest and lowest readings. This is called the diurnal variation and a 10˚C variation can be easily observed. The annual temperature was between 27˚C while the daily minimum

and maximum are 23˚C and 32˚C, respectively. **Figure 4.20** exhibits the annual temperature between 2003 and 2012. It also shows the annual maximum, minimum and temperature at 8 am and 2pm.
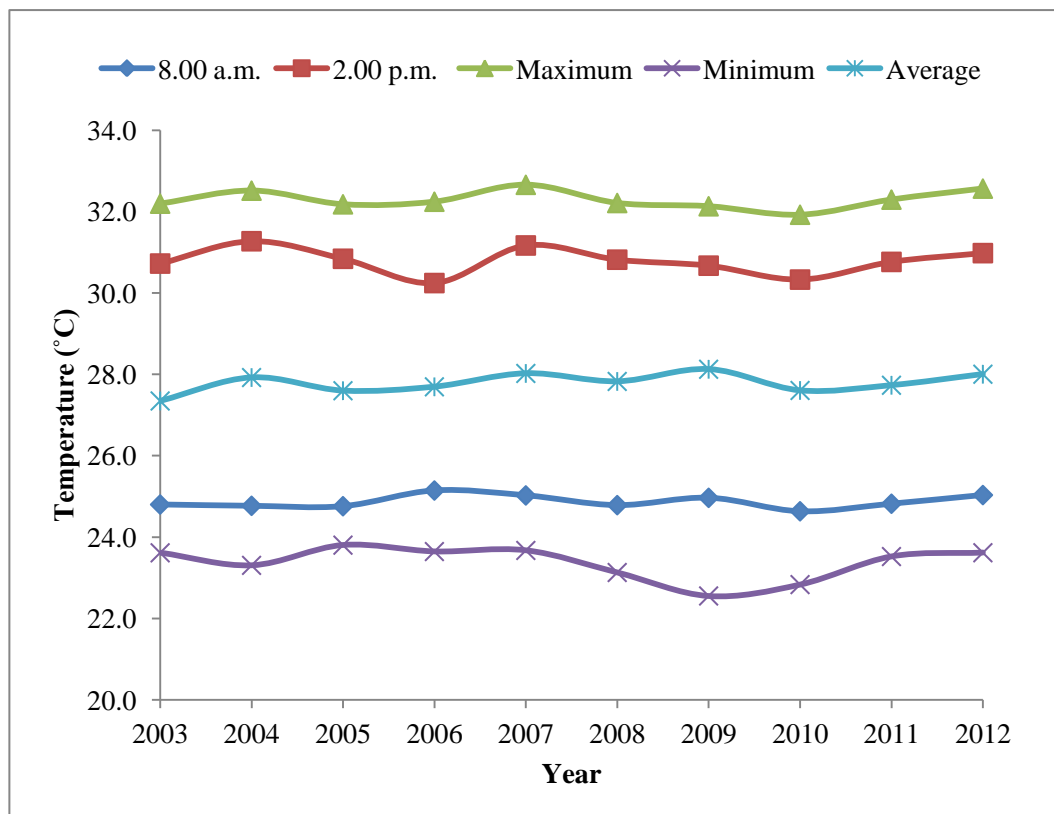

Figure 4.20: Annual temperature at JSL from 2003 to 2012

In **Figure 4.21**, it is visible that May and June have higher temperature range as compared to other months while, October to January have slightly lower temperature. The higher temperature is normally attributed to less rainfall whereas the lower temperature coincides very well with the end of the year rainy season in Malaysia. From the graph it is also apparent that the monthly average temperature ranges between 26 to 28˚C, with minimum temperature between 22 to 24˚C and the maximum temperature is

between 31 to 33 ˚C. Malaysia has two monsoon seasons, the Northeast Monsoon during the month of October to December (cold and wet) and the Southwest Monsoon during the month of July to September (hot and dry) (MetMalaysia,2013). This is in contrasts with the wide temperature ranges (minus to plus degree of Celsius) in the mid-latitude countries (Tecle *et al.*, 2009; Fourie & Morris, 2004).
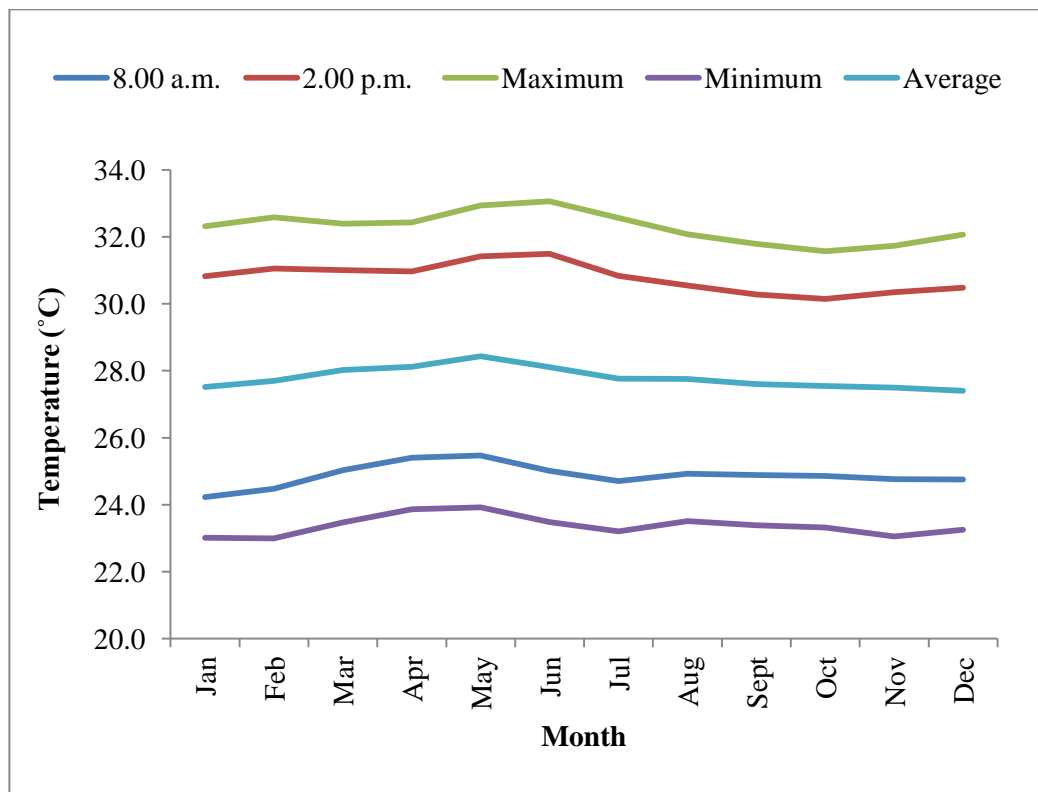

Figure 4.21: Monthly mean temperature at JSL from 2003 to 2012

4.11.3 Atmospheric humidity pattern at JSL

The atmospheric humidity is reflected on the moisture content of the air. In a tropical country like Malaysia, the humidity level is normally beyond 70%. However during certain months with less rainfall, very low humidity level can be observed. **Figure 4.22**

shows the monthly humidity observed at JSL. The humidity shows an increasing trend, reflecting the monsoon season with heavy episodes of rainfall at the end of the year. The monthly humidity ranges from 64.8% to 85% (MetMalaysia, 2013).
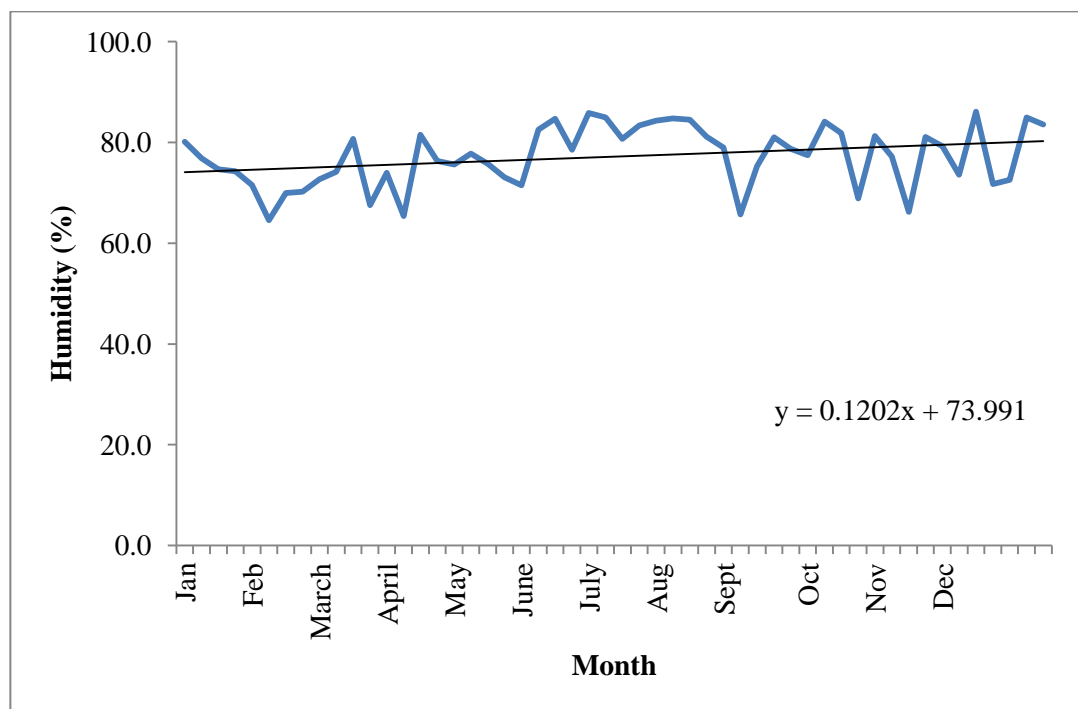

The equation shown on the figure:

$$y = 0.1202x + 73.991$$

Figure 4.22: Monthly mean humidity pattern at JSL from 2003 to 2012

4.11.4 Atmospheric pressure at JSL

The atmospheric pressure at JSL is shown in **Figure 4.23**. The graph does not show any significant pattern in the atmospheric pressure but only a slight increase is noticeable throughout the months. The mean monthly atmospheric pressure in JSL ranged from 1005 to 1011 hPa within a year (MetMalaysia, 2013). In addition to being a tropical country, Malaysia is subjected to very little variability in terms of weather. Rain and dry

spells only cannot cause abrupt changes in atmospheric pressure like in the temperate or mid-latitude countries. According to Gebert & Groengroeft (2006), atmospheric pressure in a Hamburg Landfill in Northern Germany varied between 1000 to 1020 hPa and had a significant impact on its LFG emission.
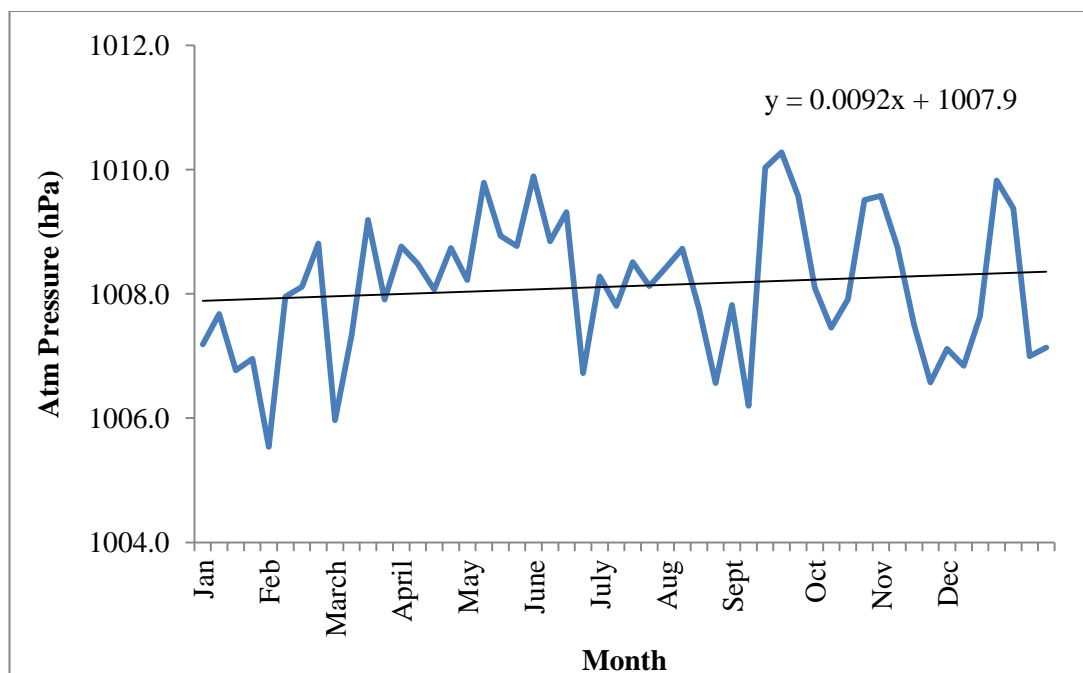
Figure 4.23: Monthly mean atmospheric pressure at JSL from 2003 to 2012

4.12   Effects of meteorological parameters on surface emission of CH$_4$

The effects of meteorological parameters on the CH$_4$ surface emission was studied during both dry and wet period. Weekly readings of meteorological parameters and CH$_4$ flux measurement were used for comparison. Regression analysis at 95% Confidence Interval was done to test the significance of each correlation, R^2.

4.12.1 Influence of rainfall on CH$_4$ flux

Figure 4.24 shows the correlation between rainfall and CH$_4$ flux during the wet period. From the graph it is evident that there is a positive linear relationship between the two parameters ($R^2 = 0.6$). This indicates that the CH$_4$ flux emission increases with the increase in rainfall amount. The result is in agreement with Wangyao et. al. (2010), who had measured five to six times higher CH$_4$ flux emission during the rainy season as compared to the winter and summer seasons in Thailand.

However, Fourie & Morris (2004) had a contradicting result while measuring CH$_4$ flux from a landfill in a semi-arid climate. The CH$_4$ flux during winter (cold and dry) was higher than in summer (hot and wet). Semi-arid climate is a dry climate where the evaporation and transpiration rates exceed the amount of rainfall (Ahrens, 2005). Therefore, for this study the results of Wangyao *et al.,* (2010) is more applicable as the climatic condition of Thailand is almost similar to Malaysia (Ahrens, 2005; Tick & Samah, 2004).
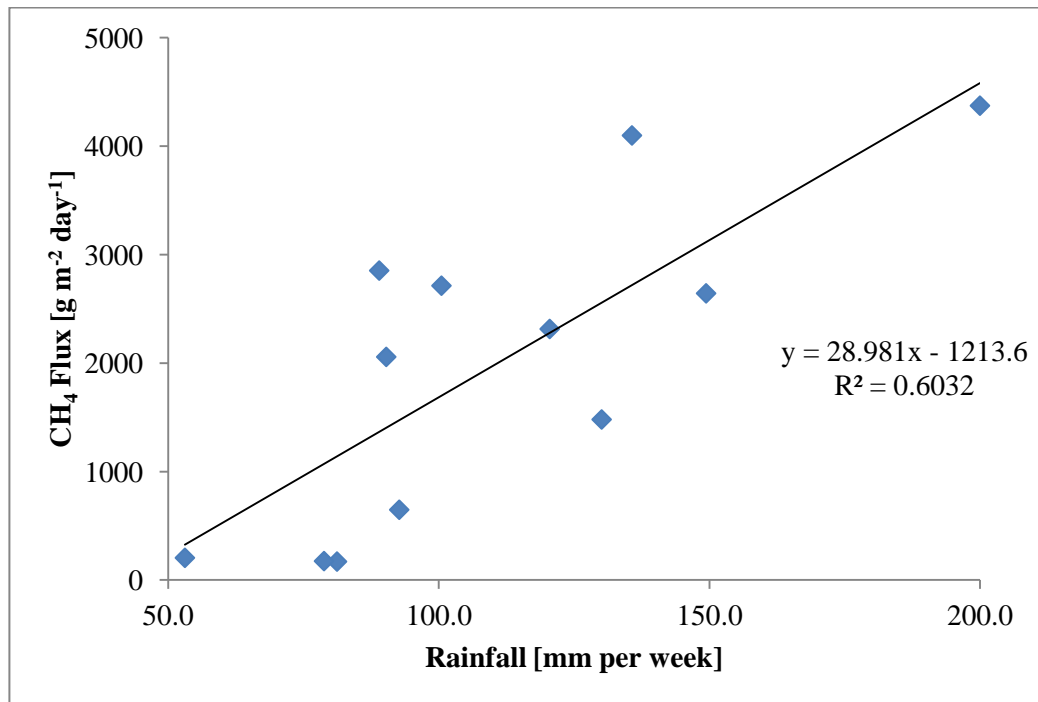
Figure 4.24: CH$_4$ emission at JSL as a function of rainfall and CH$_4$ flux during wet period

In **Figure 4.25**, a weak negative correlation ($R^2 < 0.2$) was observed between the rainfall and CH$_4$ flux emission during the dry period. As discussed earlier, visible cracks in the landfill surface would have retarded the CH$_4$ content within the landfill (Spokas *et al.*, 2003), thus lowering the surface flux emission. Besides that, the infiltration of O$_2$ through the cracks would have promoted higher levels of CH$_4$ oxidation on landfill cover, hence again reducing the surface flux emission (Fouris & Morries, 2004). Therefore, these two reasons are indeed possible explanation as to why the CH$_4$ flux emission shows a negative trend although there is a slight increase in the rainfall amount. In conclusion, the surface emission of CH$_4$ was higher during the wet period than the dry period.
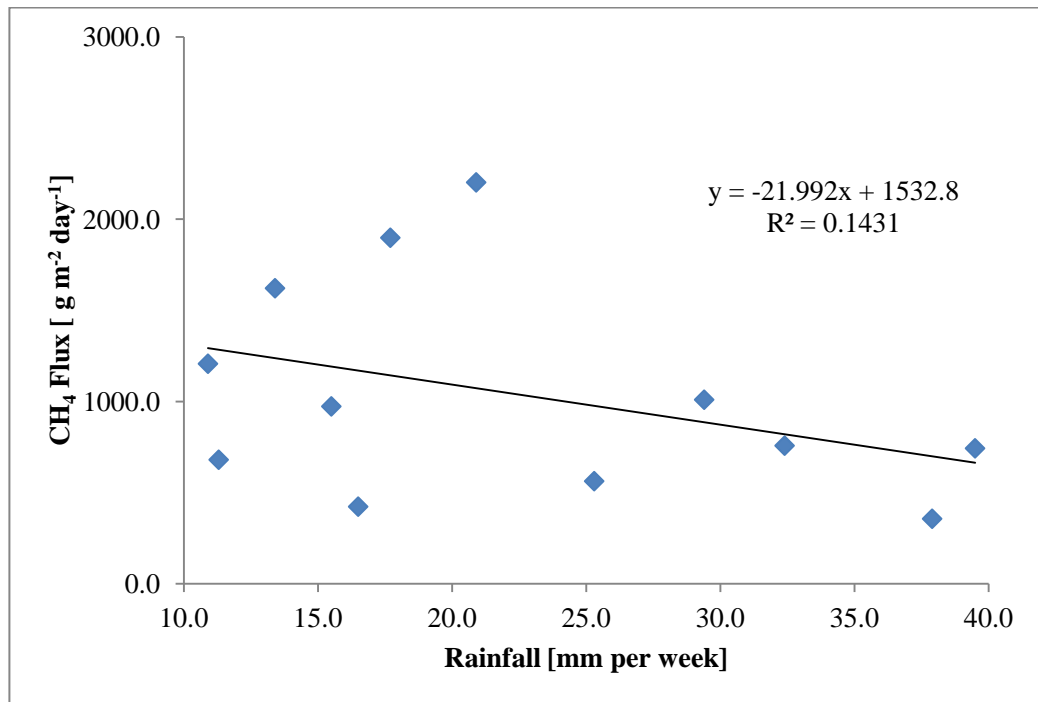
Figure 4.25: CH_4 emission at JSL as a function of rainfall and CH_4 flux during dry period

4.12.2 Influence of ambient temperature on CH_4 Flux

Figure 4.26 shows the temperature effect on CH_4 flux emission during the wet period. The temperature values too had a good correlation with the CH_4 flux emission ($R^2 \approx 0.9$) as in the rainfall pattern. However, it showed a negative trend displaying that CH_4 flux emission decreases with the rise in temperature. There was a notable sharp drop (-1282.4 g of CH_4 m^{-2} day^{-1} / °C) in the CH_4 flux emission when there was a temperature intrusion. Although this result contradicts with the findings of Wang *et. al.* (2012) and Robinson (2007), it fits very well with the increase in the rainfall amount. Hence, as rainfall increases the temperature decreases and vice-versa.
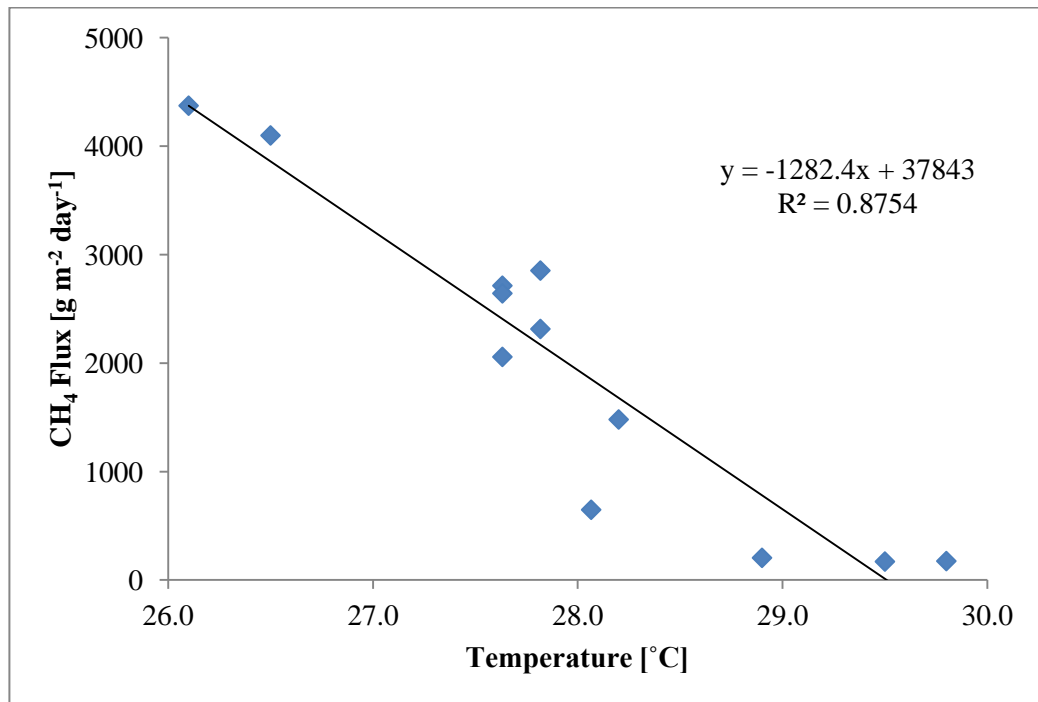
Figure 4.26: CH$_4$ emission at JSL as a function of temperature and CH$_4$ flux during wet period

The results on influence of temperature on the CH$_4$ flux emission showed a positive correlation during the dry period (Figure 4.27). The dry period had a weaker correlation as compared to the wet season but in a positive trend. The growth rate for flux and temperature during the dry period was at 903.3 g of CH$_4$ m^{-2} day^{-1} / ˚C.
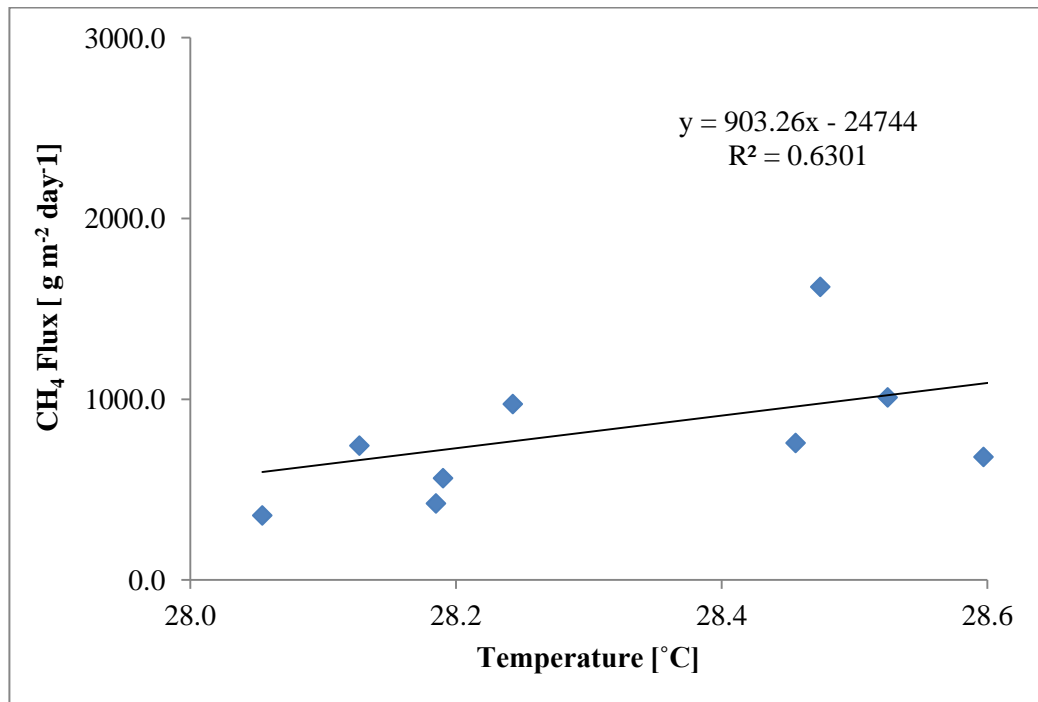
Figure 4.27: CH_4 emission at JSL as a function of temperature and CH_4 flux during dry period

In conclusion, it is difficult to prove statistically that temperature had an influence on CH_4 flux emission in JSL as both period of measured ambient temperature showed contradicting results with previous research findings. The implication could be due to the fact that Malaysia's temperature does not vary abruptly to cause significant changes in the CH_4 flux emission. Another point to consider is also the variation of temperature within a landfill is less than the outside temperature.

4.12.3 Influence of atmospheric humidity on CH_4 Flux

Humidity or moisture content in the atmosphere is inversely proportioned to the air temperature. The humidity drops when temperature increases (Ahrens, 2005). In a study

by Tecle *et al.,* (2008), it was concluded that there were no significant relationship between humidity (moisture content) and CH_4 surface emission (volumetric methane). Similar results were also reflected in the case of JSL (**Figures 4.28** and **4.29**). From the correlation analysis it can be statistically concluded that humidity did not influence the CH_4 flux emission in JSL during both the wet and dry period ($R^2<0.5$). The correlation is not significant.

The plot shows $y = 4\text{E-}15x^{9.2396}$ and $R^2 = 0.2395$, with axes "CH$_4$ Flux [g m^{-2} day^{-1}]" (0 to 5000) versus "Atmospheric Humidity (%)" (65.0 to 85.0).
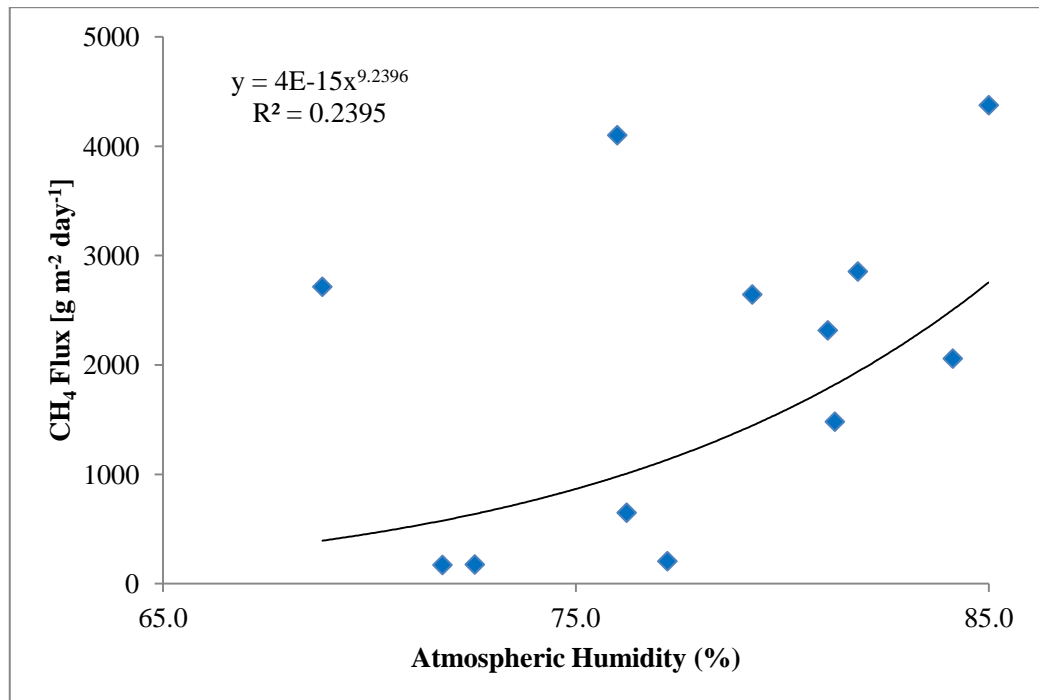
Figure 4.28: CH_4 emission at JSL as a function of humidity and CH_4 flux during wet period
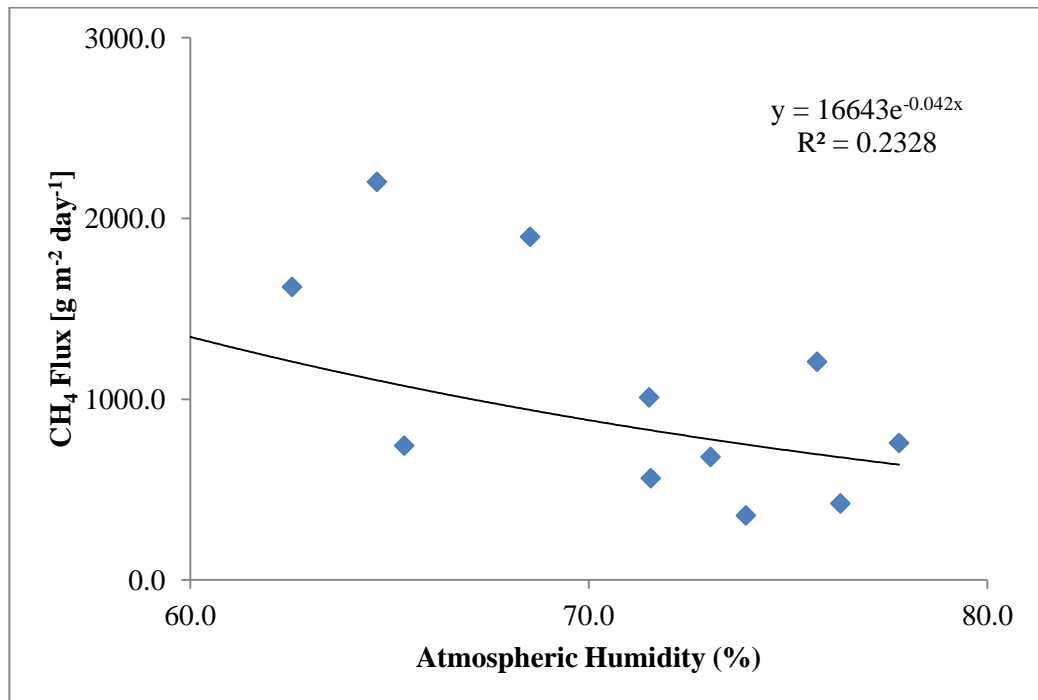
Figure 4.29: CH_4 emission at JSL as a function of humidity and CH_4 flux during dry period

4.12.4 The influence of atmospheric pressure

In 2003, Czepial *et al.* had studied the influence of atmospheric pressure on landfill CH_4 emission using tracer emission measurement technique. The study was focused at Nashua Municipal landfill located in northern US which had an atmospheric pressure range of 1006 to 1024 hPa. From the study, it was concluded that the surface emissions were inversely proportional (negatively correlated) to atmospheric pressure. Similar trend was observed on the influence of atmospheric pressure on surface CH_4 flux emission in JSL for both wet and dry period as shown in **Figure 4.30** and **Figure 4.31**. However, since the correlation of coefficient is very weak ($R^2 < 0.5$) it is impossible to prove that atmospheric pressure influences on the CH_4 emission in JSL. According to Gebert & Groengroeft (2006), atmospheric pressure on the Earth's surface is driven by

the following processes; (1) passage of high and low pressure systems; (2) warming and cooling of air caused by seasonal variation and solar irradiation; (3) auto-oscillation of air. Since Malaysia is, situated in the Equator (Ahrens, 2005; Tick & Samah, 2004) and is only affected by the latter two processes, hence this gives a good explanation to why JSL does not have a huge difference in the atmospheric pressure. This could drive the movement of CH_4 from the ground to the atmosphere.
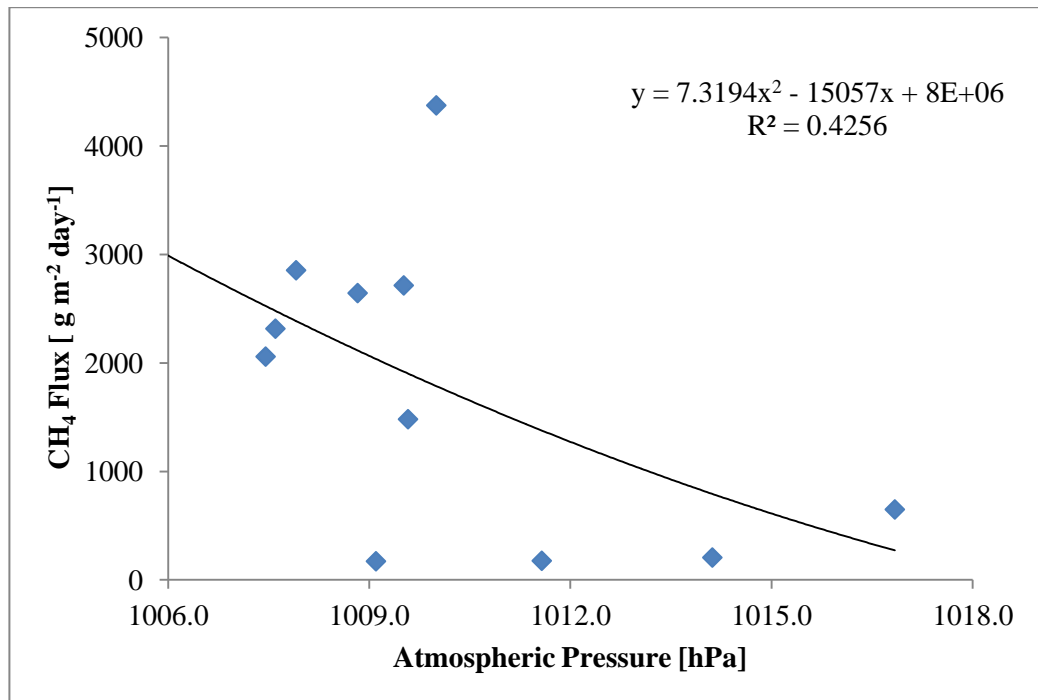
Figure 4.30: CH_4 emission at JSL as a function of atmospheric pressure and CH_4 flux during wet period
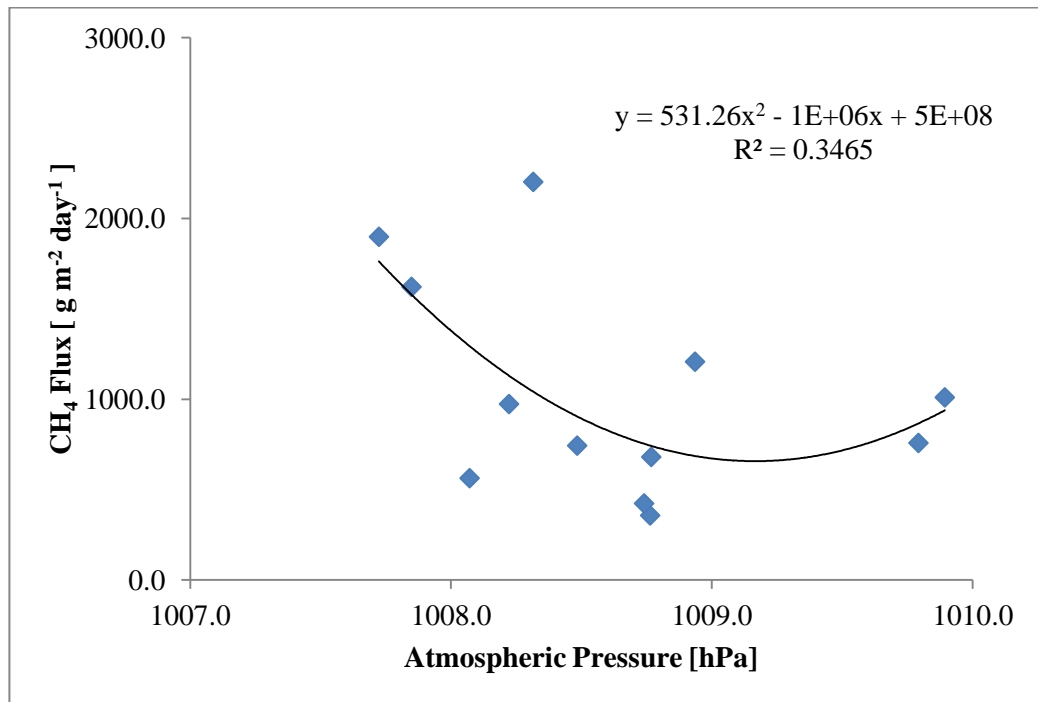
Figure 4.31: CH_4 emission at JSL as a function of atmospheric pressure and CH_4 flux during dry period

As a general conclusion on the influence of meteorological parameters on CH_4 surface flux emissions at JSL, based on the data collected only rainfall had a significant impact on the flux emissions. Parameters such as the temperature and atmospheric humidity were inter-related to rainfall but did not have major influences on the emission rates. Atmospheric pressure was found to be the least significant among the meteorological parameters to influence the amount of CH_4 surface flux generated. More important factors like pressure gradient within the landfill soil, waste degradation rate, LFG collection and microbial activity are believed to contribute significantly to the surface flux emission of CH_4 (Scheutz *et al.*, 2009; Stern *et al.*, 2007; Themilis & Ulloa, 2007).

4.13 Bioremediation of landfill CH$_4$ using Biocover

Part of this study also focused on the bioremediation of landfill CH$_4$ using biocover as an effort of climate change mitigation of CH$_4$ gas. For this purpose a landfill biocover which enables CH$_4$ oxidation through microbial activity was designed. The biocover material was made using organic waste products such as grass clippings, cow manure and brewery spent grain (BSG). Two types of biocover materials investigated as biocover were (1) BSG and compost mix and (2) composted BSG.

4.13.1 The Physico-chemical Characteristics of the Biocover Material

Physico-chemical analyses were performed on the raw biocover material of fresh BSG and compost. **Tables 4.9, 4.10 and 4.11** show the properties of the materials including the standard method used for the analysis. A study by Humer & Lechner (1999) indicated that CH$_4$ emission in a cover material was controlled by moisture content. According to Hilger & Humer (2003) and Wilshusen *et al.*, (2004) compost has good water holding capacity needed to optimize CH$_4$ oxidation. CH$_4$ oxidation becomes limited due to physiological stress to methanotrophs if moisture content is low (Pawloska, 2008). Thus, both BSG and compost with more than 60% moisture content were favourable for methanotrophs growth. Furthermore in a study by Mussatto *et. al.*, (2006), it was indicated that the high fermentable sugar in BSG creates a favorable condition for microbial activity. Adding on to this, suitable pH is also necessary to balance the microbial population particularly for the optimization of CH$_4$ oxidation

activities. While Moldes *et al*. (2007) also suggested that the pH should be neutral to slightly acidic in order to optimize CH_4 oxidation.

Organic matter improves soil properties and serves as the main carrier for the methanotrophic microorganisms as stated by Chanton & Liptay (2000). It creates a conductive environment for potential growth of microbes and both materials (grass clipping and cow dung, in this study) had more than 60% of organic matter. As mentioned earlier, BSG is high in N source and to be used for the synthesis of cellular material, amino acids and protein (Graves & Hattavier, 2000). While, compost serves to provide C source which is used as energy for the growth of microbes. Thus, it is important that the C:N ratio between the materials is balanced to achieved maximum CH_4 oxidation. In addition, the C:N ratio also determines the maturity of the compost used. From literature, the ranges of C:N ratio was between 10:1 to 30:1 (Graves & Hattavier, 2000).

Minerals such as K, Ca, Fe, Mg and P showed a marked difference between both the materials. Increase or decrease of these macronutrients for plants to promote or hinder the growth of plants. However, its potential for methanotrophic growth is still unclear, except as mentioned by Scheutz *et al,*. (2009) that CH_4 oxidation will be higher when Cu content is low considering the fact that methanotrophs produce a soluble enzyme (sMMO) in the absence of Cu.

Table 4.9: Physico-chemical properties of raw BSG

Test Parameter	Test Method	Raw BSG
Moisture content (%)	ASTM 2004	70.58 ± 0.14
pH	ASTM 2004	4.41 ± 0.12
Organic matter (%)	ASTM 830-97	73.60 ± 0.10
Total C (%)	ASTM 777-87 (96)	15.80 ± 0.10
Total N (%)	ASTM E778-87	1.07 ± 0.10
C:N Ratio	USEPA 3050B	15:1
Total K (ppm)	ASTM E926-94	69.5 ± 0.10
Ca (ppm)	USEPA 3050B	1389 ± 5.0
Fe (ppm)	USEPA 3050B	111.8 ± 1.0
Mg (ppm)	USEPA 3050B	594.6 ± 1.0
Na (ppm)	USEPA 3050B	1.75 ± 0.10
Total P (ppm)	ASTM D 5198-92	771.4 ± 0.5
Zn (ppm)	USEPA 3050B	19.7 ± 0.10
Pb (ppm)	USEPA 3050B	2.65 ± 0.10
Total S (ppm)	ASTM D 3177	185 ± 5.0
Al (ppm)	USEPA 3050B	6.80 ± 0.10
Cu (ppm)	USEPA 3050B	4.81 ± 0.10

Table 4.10: Physico-chemical properties of Compost from Grass Clippings and Cow Manure

Test Parameter	Test Method	Compost
Moisture content (%)	ASTM 2004	62.17 ± 0.14
pH	ASTM 2004	6.33 ± 0.12
Organic matter (%)	ASTM 830-97	63.60 ± 0.10
Total C (%)	ASTM 777-87 (96)	20.30 ± 0.10
Total N (%)	ASTM E778-87	1.20 ± 0.10
C:N Ratio	USEPA 3050B	17:1
Total K (ppm)	ASTM E926-94	690.9 ± 0.10
Ca (ppm)	USEPA 3050B	372.7 ± 5.0
Fe (ppm)	USEPA 3050B	23.8 ± 1.0
Mg (ppm)	USEPA 3050B	55.0 ± 1.0
Na (ppm)	USEPA 3050B	0.75 ± 0.10
Total P (ppm)	ASTM D 5198-92	183.6 ± 0.5
Zn (ppm)	USEPA 3050B	2.67 ± 0.10
Pb (ppm)	USEPA 3050B	ND (< 0.01)
Total S (ppm)	ASTM D 3177	145 ± 5.0
Al (ppm)	USEPA 3050B	8.51 ± 0.10
Cu (ppm)	USEPA 3050B	0.627 ± 0.10

Table 4.11: Physico-chemical properties of Composted BSG

Test Parameter	Test Method	Compost BSG
Moisture content (%)	ASTM 2004	60.6 ± 0.12
pH	ASTM 2004	5.33 ± 0.10
Organic matter (%)	ASTM 830-97	50.6 ± 0.5
Total C (%)	ASTM 777-87 (96)	28.5 ± 0.3
Total N (%)	ASTM E778-87	1.23 ± 0.16
C:N Ratio	USEPA 3050B	23:1
Total K (ppm)	ASTM E926-94	890.9 ± 0.2
Ca (ppm)	USEPA 3050B	572.7 ± 0.4
Fe (ppm)	USEPA 3050B	273.8 ± 0.5
Mg (ppm)	USEPA 3050B	861.0 ± 0.6
Na (ppm)	USEPA 3050B	6.35 ± 0.21
Total P (ppm)	ASTM D 5198-92	483.6 ± 0.3
Zn (ppm)	USEPA 3050B	24.67 ± 0.15
Pb (ppm)	USEPA 3050B	ND (< 0.01)
Total S (ppm)	ASTM D 3177	147 ± 5.0
Al (ppm)	USEPA 3050B	86 ± 2.0
Cu (ppm)	USEPA 3050B	12.5 ± 0.7

4.13.2 Result of the Batch Experiments Stage 1:

The best BSG to compost ratio

From BSG to compost mixture batch experiment, the best ratio with highest CH_4 oxidation was 7:3. **Figure 4.32** shows CH_4 oxidation among the different ratio of BSG to compost. The error bars indicate the standard deviation between the duplicates of each set of experiment. The 7:3 ratio had 65% CH_4 oxidation while only BSG without any compost mix showed the lowest CH_4 oxidation of 6%. Previous studies have proven that BSG can be applied to improve soil quality (Mussatto *et. al.*, 2006), used as fertilizer for egg-plants (Moyin-Jesu, 2007) and cultivation of oyster mushroom (Wang *et. al.*, 2001). However, BSG always have to be mixed with other materials for any reaction to take place. This confirms that BSG by itself is less reactive during direct application.

Adding on, the lower CH_4 oxidation rate could be attributed by the low C source and high Cu slows the methanotrophs growth. When compost that is rich in nutrients was added to BSG to oxidize CH_4, it accelerates the microbial growth which increased CH_4 oxidation. However, only suitable amount of compost can be added to help in CH_4 oxidation (SivaShangari & Agamuthu, 2012). This is evident in this study when ratios of BSG to compost ratio of 9:1 and 1:9 were not able to achieve high CH_4 oxidation. The effect of C:N was identified as one of the reason for such cases.

From **Figure 4.32**, it was noted that the maximum CH_4 oxidation achieved by 20g of biocover material was only 67%. Therefore, the experiment was repeated with more biocover material and the results are shown in **Table 4.12**. From the results it is evident that the highest CH_4 oxidation of 87.8% occurred when 40g of biocover material was used. 50g and 60g of biocover material showed lower CH_4 oxidation as compared to the rest of material amount used.
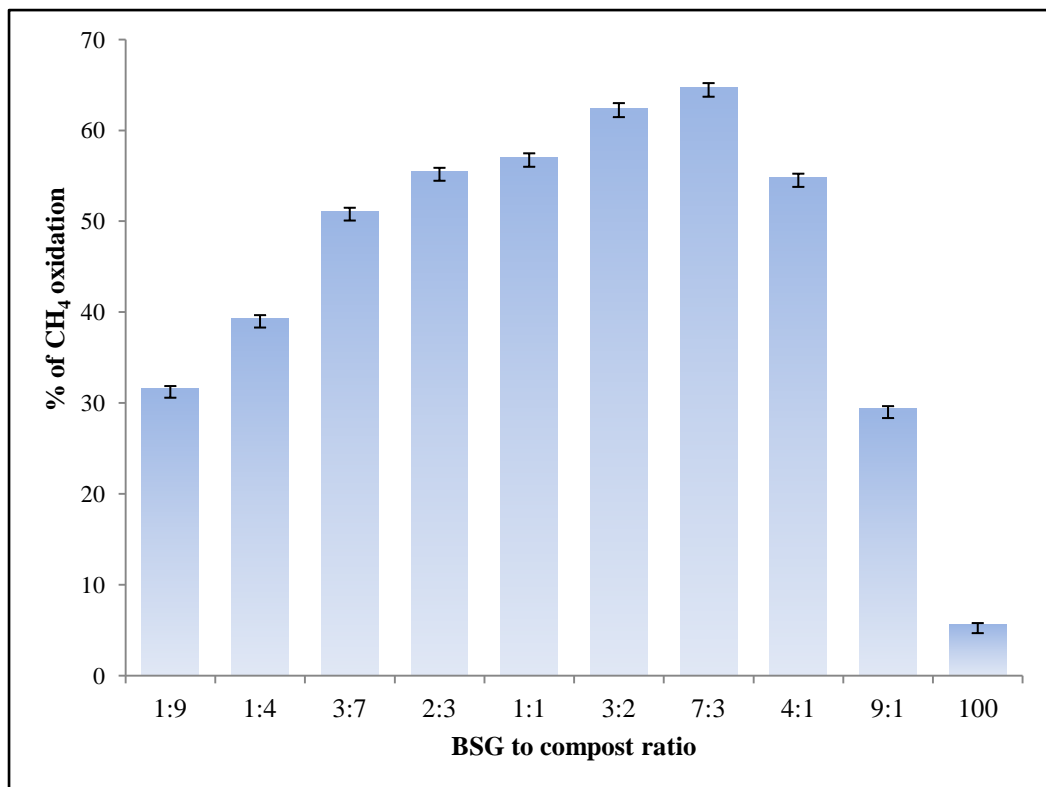

Figure 4.32: Results of batch experiment set up in different ratio

Composted BSG as biocover material

Composted BSG showed 30% of CH_4 oxidation when tested. However, it was further subjected to parametric testing to investigate if any parameters could enhance CH_4 oxidation using this material.

Table 4.12: CH_4 oxidation by different amount of biocover material

Amount of biocover material used (g)	Average CH_4 oxidation (%)	Standard deviation
30	70.9	± 0.4
40	87.8	± 2.3
50	60.5	± 1.2
60	57.4	± 0.6

4.13.3 Result of the Batch Experiments Stage II:

The optimum parameter from Box-Behnken Experimental Design

The expert design software had designed 17 experimental runs instead of 27 as three factors were chosen for analysis. The experimental design as provided by the software and the percentage of CH_4 oxidation achieved by each experimental run is tabulated in **Tables 4.13** and **4.14**. The experimental runs were used for both the Biocover material, the BSG and compost mix, as well as, the composted BSG. Both has identical runs but only differed in the amount of CH_4 oxidation.

Table 4.13: Experimental design runs and percentage of CH_4 oxidation for BSG and compost mix as biocover material

Run	pH	Moisture Content (%)	Temperature (°C)	CH_4 Oxidation (%)
1	6	50	55	54.5
2	6	65	40	85.0
3	6	65	40	86.0
4	8	50	40	15.5
5	6	50	25	46.1
6	6	80	55	40.5
7	8	65	55	20.5
8	8	65	25	12.0
9	6	80	25	27.0
10	6	65	40	87.0
11	6	65	40	80.4
12	4	80	40	36.4
13	6	65	40	86.0
14	4	65	55	61.0
15	8	80	40	10.0
16	4	50	40	59.5
17	4	65	25	42.5

Table 4.14: Experimental design runs and percentage of CH_4 oxidation for composted BSG as biocover material

Run	pH	Moisture Content (%)	Temperature (˚C)	CH₄ Oxidation (%)
1	6	50	55	19.6
2	6	65	40	21.0
3	6	65	40	12.0
4	8	50	40	16.5
5	6	50	25	25.2
6	6	80	55	24..5
7	8	65	55	16.0
8	8	65	25	13.6
9	6	80	25	20.2
10	6	65	40	19.4
11	6	65	40	17.4
12	4	80	40	22.0
13	6	65	40	21.9
14	4	65	55	25.8
15	8	80	40	25.8
16	4	50	40	27.3
17	4	65	25	13.3

By applying the multiple regression analysis on the design matrix and results given in **Tables 4.13** and **4.14,** the following second-order polynomial equations were obtained for the percentage of CH_4 oxidation:

1) BSG and Compost mix:

$$CH_4 \text{ oxidation (\%)} = 84.90 - (17.78 * A) - (7.70 * B) + (6.03 * C) + (4.53 * A * B) - (2.68 * A * C) - (31.36 * A^2) - (23.31 * B^2) - (19.71 * C^2)$$

… **Eq (4.1)**

2) Composted BSG :

$$CH_4 \text{ oxidation (\%)} = 98.40 - 12.96 * A - 1.38 * B - 0.08 * C + 0.20 * A * B \\ 5.66092E{-}003 * B * C$$

… **Eq (4.2)**

Where *A* is pH, *B* is moisture content and *C* is temperature.

An ANOVA for the regression model in **Equation 4.1** and **4.2** was done seperately to determine the impact of independent variables on the dependent variable (Sen & Swaminathan, 2004). As shown in **Tables 4.15** and **4.16**, the quadratic model was highly significant as it was evident from Fisher's F-test (F model = 322.85) with a low probability value (*p*-value model > F = 0.0001) as suggested by several authors who have applied RSM modelling in their work (Mukherjee *et al.*, 2013; Yetilmezsoy *et al.*, 2009; Liu *et al.*, 2004). Furthermore, the calculated F value (F_{cal} = 322.85 for **Eq. 4.1**) and (F_{cal} = 19.194 for **Eq. 4.2**) was definitely greater than the tabulated F value ($F_{0.05,9,7}$

= F_{tab} = 3.68 for **Eq. 4.1 & 4.2**) at 95% confidence interval. Since $F_{cal}>F_{tab}$ (322.85> 3.68 for **Eq. 4.1** and 19.19 > 3.68 for **Eq. 4.2**), the regression model has a very high degree of adequacy that from Fisher's F-test it can be concluded that it only has 5% of a model value of the test that could occur due to noise which represents the homogeneity of variance of CH_4 oxidation by BSG and compost mixture.

Table 4.15: Statistical analysis of ANOVA for CH_4 oxidation by BSG and compost mixture

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	12367.50	8	1545.94	322.85	< 0.0001	significant
A-pH	2527.50	1	2527.60	527.86	< 0.0001	
B-Moisture Content	474.32	1	474.32	99.06	< 0.0001	
C-Temperature	290.40	1	290.40	60.65	< 0.0001	
AB	81.90	1	81.90	17.10	0.0033	
AC	28.62	1	28.62	5.98	0.0403	
A^2	4141.50	1	4141.50	864.90	< 0.0001	
B^2	2288.31	1	2288.31	477.88	< 0.0001	
C^2	1636.14	1	1636.14	341.69	< 0.0001	
Residual	38.31	8	4.79			
Lack of Fit	12.11	4	3.03	0.46	0.7635	not significant
Pure Error	26.20	4	6.55			
Cor Total	12405.81	16				
Std. Dev.	2.19	R-Squared		0.989		
Mean	49.89	Adj R-Squared		0.971		
C.V. %	4.39	Pred R-Squared		0.964		
PRESS	131.76	Adeq Precision		47.498		

Table 4.16: Statistical analysis of ANOVA for CH_4 oxidation of composted BSG

Source	Sum of squares	df	Mean square	F-value	p-value Prob > F	
Model	300.952	5	60.190	19.194	< 0.0001	significant
A-pH	0.499	1	0.499	0.159	0.6977	
B-Moisture Content	2.294	1	2.294	0.732	0.4106	
C-Temperature	151.366	1	151.366	48.269	< 0.0001	
AB	140.303	1	140.303	44.741	< 0.0001	
BC	6.489	1	6.489	2.069	0.1781	
Residual	34.495	11	3.136			
Lack of Fit	29.389	7	4.198	3.289	0.1334	not significant
Pure Error	5.106	4	1.276			
Cor Total	335.446	16				
Std. Dev.	1.771	R-Squared		0.897		
Mean	19.866	Adj R-Squared		0.850		
C.V. %	8.914	Pred R-Squared		0.676		
PRESS	108.518	Adeq Precision		12.277		

The accuracy of prediction of CH_4 oxidation by this model is measured by the predicted R^2. Mukherjee *et al.*, (2013) had reported that the predicted R^2 and adjusted R^2 values must be within approximately 0.2 difference so that there will be no error in the model. In this study, the predicted R^2 value of CH_4 oxidation was within reasonable agreement with the adjusted R^2 with only 2.2% (for BSG and compost mix) and 1.8% (for composted BSG) of the total variation.

The signal to noise ratio is a measure of the range of predicted CH_4 oxidation relative to the associated error. A desirable value of 4 or more is indicative of adequate precision and in this case the figure was 47.5 (for BSG and compost mix) and 12.3 (for composted BSG) (Mukherjee *et. al.*, 2013; Aghamohammadi *et. al.*, 2007). Moreover, a very high degree of precision and good deal of reliability of the conducted experiments were indicated by a low value of the coefficient of variation (C.V. = 4.39% for BSG and compost mix and 8.9% for composted BSG) as suggested in literature by Adinarayan & Ellaiah (2002) and Sen & Swaminathan (2004). The response surface plot for percentage of CH_4 oxidation for BSG and compost mix is shown in **Figures 4.33** and **4.34**. While, **Figure 4.35** is for the composted BSG material.
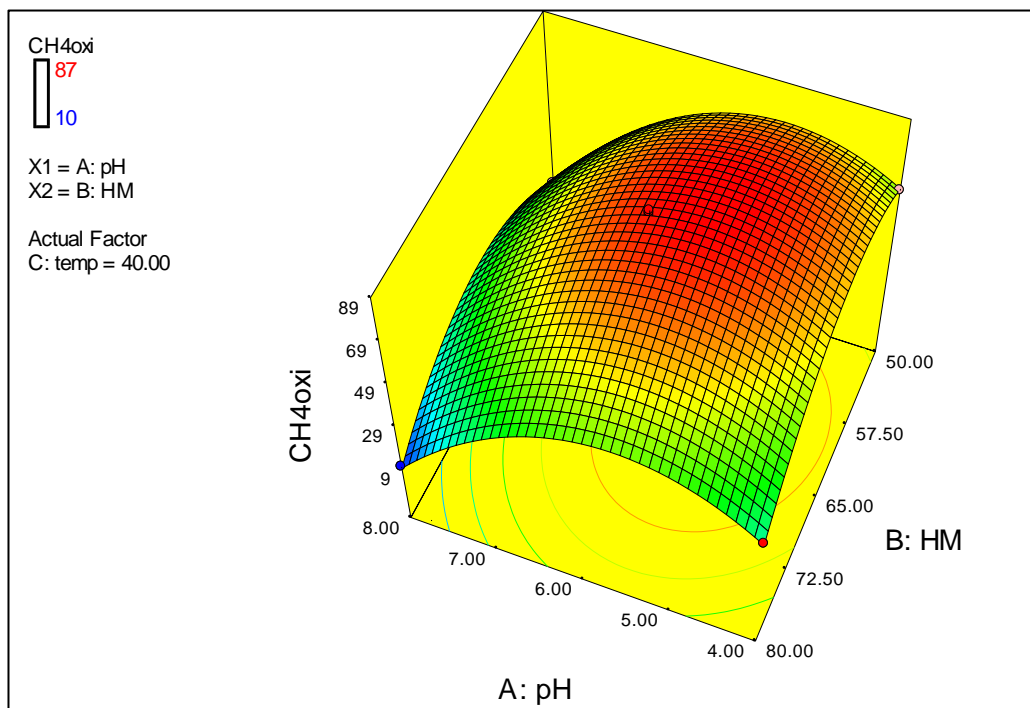

Figure 4.33: Response surface plot on CH_4 oxidation by BSG and compost mixture with response to pH and moisture content as biocover material
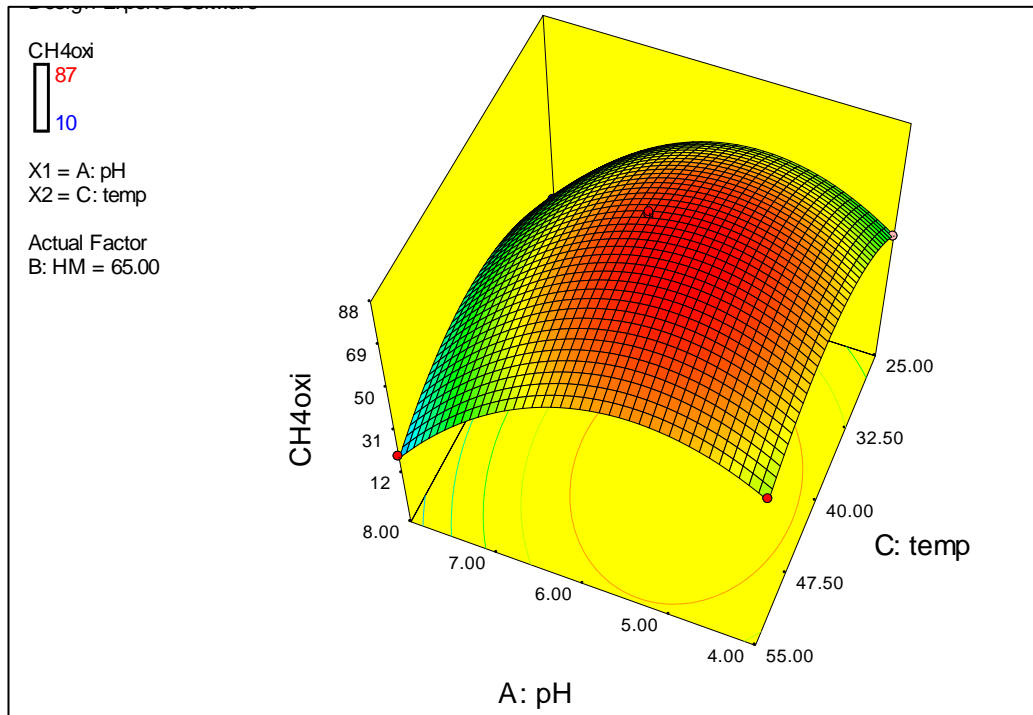
Figure 4.34: Response surface plot on CH$_4$ oxidation by BSG and compost mixture with response to pH and temperature as biocover material
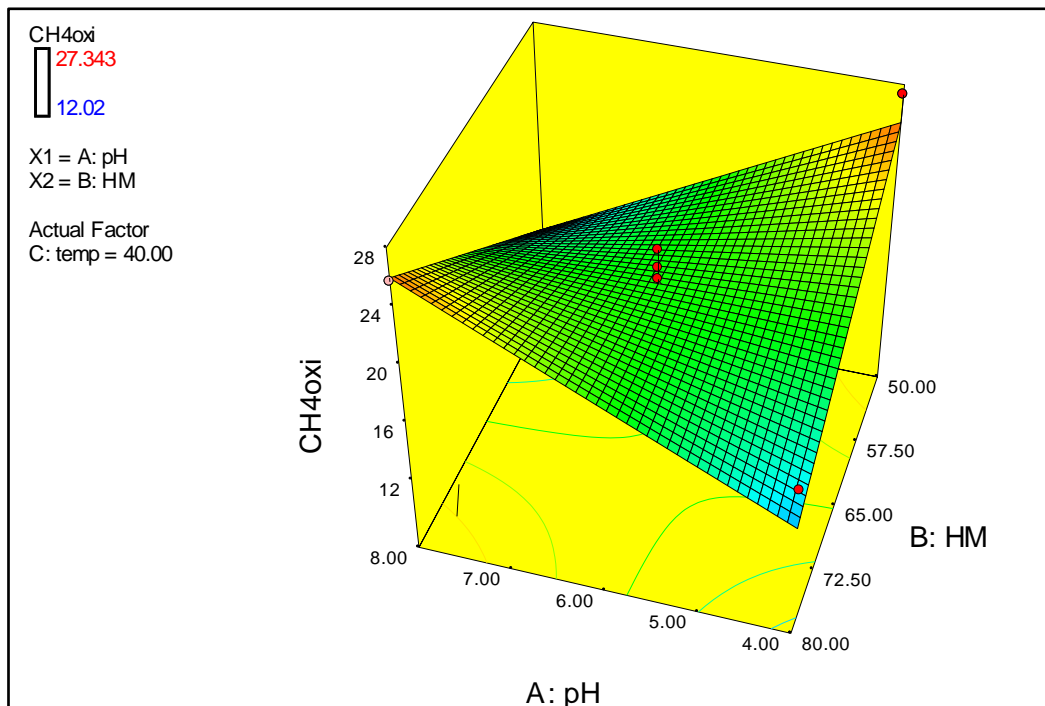

Figure 4.35: Response surface plot on CH$_4$ oxidation by composted BSG as with response to pH and moisture content as biocover material

Effect of pH

The response surface plots for percentage of CH_4 oxidation by pH, moisture content and temperature are shown in **Figures 4.33** and **4.34** for BSG and compost mix. All three parameters typically followed parabolic curves, with reduced CH_4 oxidation under low conditions and increased rate to the high condition (Chiemchaisri *et al.*, 2012). In both contour plots, CH_4 oxidation increased as pH increased from pH 4 to pH 6. Thereafter, it decreased accordingly with pH increase from pH 7 to pH 8. The highest percentage of CH_4 oxidation was 87% observed at pH 6. This is in supportive with the results obtained by Moldes *et al.,* (2007) whom stated that the pH influenced CH_4 oxidation and ranged from neutral to slightly acidic situation in order to favour balanced microbial population and optimize CH_4 oxidation activity. It is an important factor that has direct implications on methanotrophic activity in a biocover system (Jayanthi, 2013). In **Figure 4.35**, CH_4 oxidation increased as pH increases. However, CH_4 oxidation is not as prominent as it was in BSG and compost mix.

Effect of moisture content

In **Figure 4.34**, CH_4 oxidation gradually increased with 50 to 65% moisture content and decreased later as moisture content increased further till 80%. Moisture content of the cover soil is an important factor controlling CH_4 emissions from landfills (De Visscher *et al.*, 2001). The biocover materials ability to retain water is important in sustaining the microbial population required for CH_4 oxidation as low level of moisture content inhibits CH_4 oxidation (Humer & Lechner, 2001). While in a study by Barlaz *et al.,* (2004) on compost covers, CH_4 can also be produce if moisture content was too high.

Similar to the pH effect, CH_4 oxidation increased linearly with moisture content which is also not as prominent as it was in BSG and compost mix. The maximum CH_4 oxidation was only about 28%.

Effect of temperature

The effect of incubation temperature of the biocover material on CH_4 oxidation (**Figure 4.34**) did not show much variation in percentage of CH_4 oxidation as compared to the effect of pH and moisture content. The highest CH_4 oxidation of 70% was observed at temperature 40˚C. Moreover, according to Boeckx *et al.,* (1996) the moisture content has more influence on CH_4 oxidation activity as compared to temperature. In two separated studies by Fauziah (2009) and Pawloska (2008), it was indicated that the methanotrophic activities are very high in mesophilic conditions and temperature rise showed that the activities of bacteria become slower. Incubation of the optimum temperature of 35˚C-40˚C also showed similar trend (Jayanthi, 2013). On the other hand, temperature did not show any significant effect to CH_4 oxidation in the composted BSG.

4.14 Optimization and model validation

Optimization process of the percentage of CH_4 oxidation for BSG and compost mix was performed by a multiple response method known as desirability function (Mukherjee *et al.*, 2013). The purpose was to optimize different combinations of parameter for maximum CH_4 oxidation for the column experiment application. To obtain maximum

CH$_4$ oxidation, pH was set at 6, moisture content at 65% and temperature at 35°C (maximum average in Malaysian landfill) as shown in **Table 4.17**. Additional experiments were carried out using the optimal conditions derived in duplicates. Results were recorded in **Table 4.17** under validation. From the validation exercise, it can be concluded that the model generated CH$_4$ oxidation percentage gave an adequate prediction of the real condition with relatively small error of 3%. The model optimization process was not performed for the composted BSG due to the fact that it had poor CH$_4$ oxidation potential.

Table 4.17: Model optimization and validation

			Optimization		Validation	
pH	Moisture Content	Temperature	CH$_4$ oxidation	Desirability	CH$_4$ oxidation	Error
6	65%	35°C	83.5 %	0.97	85.5%	3%

4.15   Results of Column Experiment: Laboratory and landfill studies

The results for laboratory scale column experiment are plotted in **Figure 4.36**. It shows the initial concentration of CH$_4$ on Day 0 till Day 7 when 100% CH$_4$ oxidation efficiency was observed at all heights. 50cm height was the first to show zero CH$_4$

concentration, 5 days after exposure to CH_4 followed by the rest of the height level on day 6 and 7. It was also noticed that the concentration of CH_4 decreased with column height. Similar results were obtained by Navarani (2009), Sitiaishah (2011) and Jayanthi (2013) with compost as the main biocover material.

Figure 4.37 presents the results of landfill studies. When exposed to landfill conditions, CH_4 took slightly longer to oxidize then in the laboratory. The fastest height to achieve zero CH_4 concentration was 60 cm after 6 days of exposure. The lag in time could be due to the fact that laboratory condition is a controlled environment but this is not the case in the landfill. Temperature change between day and night as well as before and after rain could contribute to the lag in time of CH_4 oxidation. Furthermore, the complexity of LFG itself is another contributing factor. The composition of LFG changes according with the stabilisation of the waste within the landfill (Fourie & Morris, 2004).
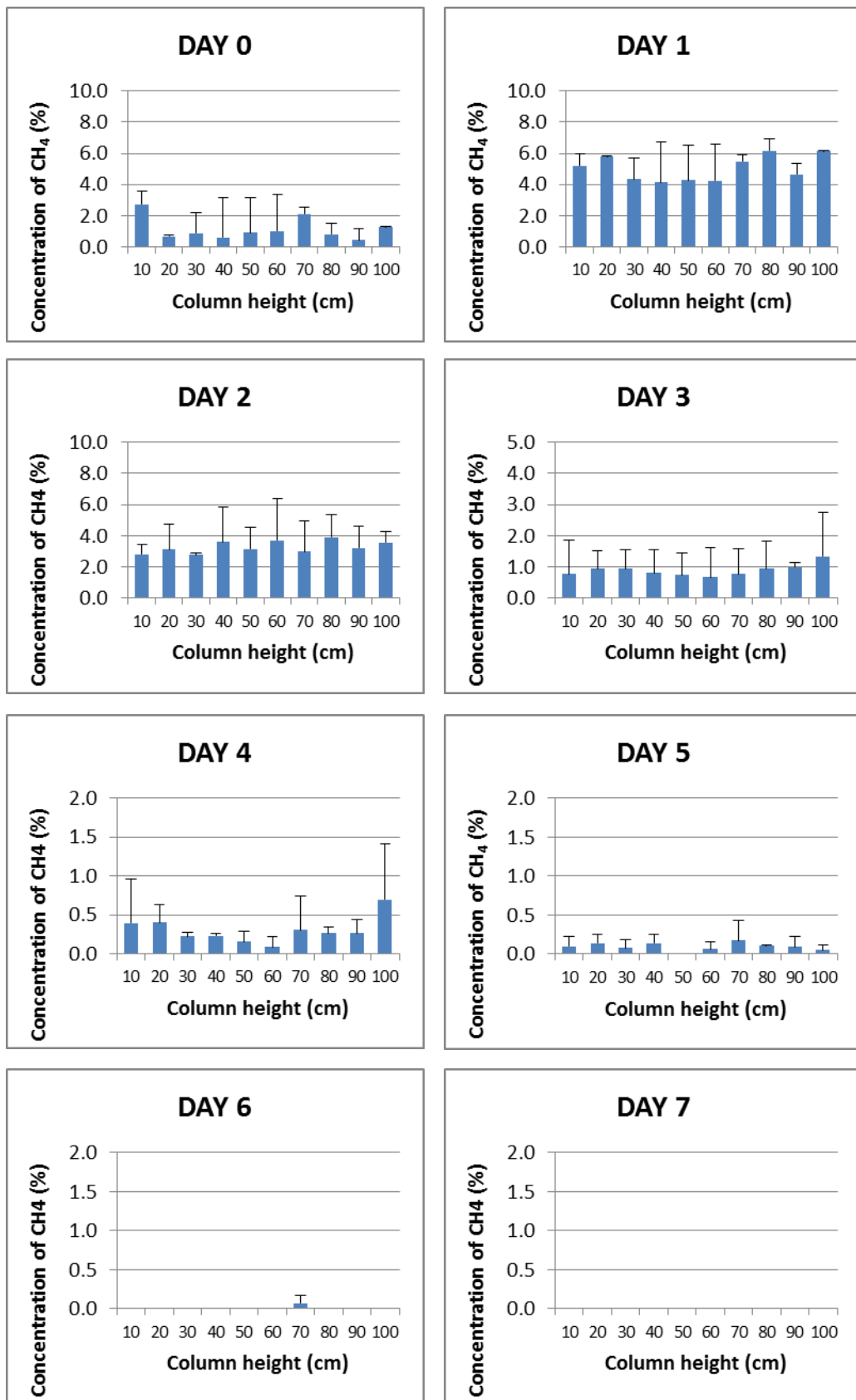
Figure 4.36: Concentration of CH_4 in column experiments performed in the laboratory. Each bar represents the average of two columns and the error bar indicates standard deviation
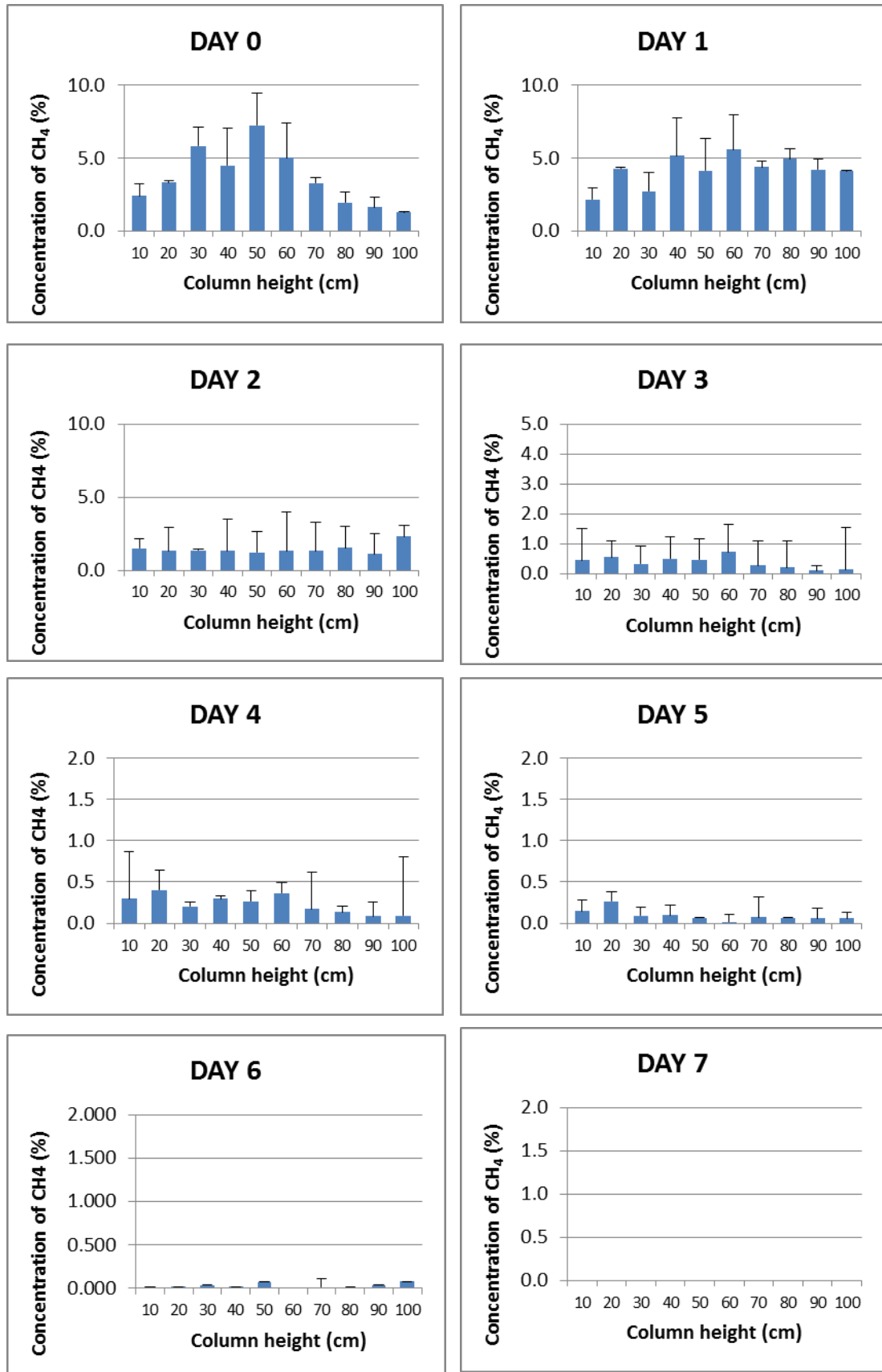
Figure 4.37: Concentration of CH_4 in column experiments performed in the landfill. Each bar represents the average of two columns and the error bar indicates standard deviation.

4.16 Conclusion for the biocover material

The optimal ratio of BSG to compost as biocover material is 7:3 with optimum parameters moisture content of 65%, pH of 6 and temperature of 35°C. The column experiments showed complete 100% CH_4 oxidation on Day 5 at 50cm height in laboratory condition and Day 6 at 60cm height in landfill condition. The results also show that both batch incubation experiments and column experiments enhanced CH_4 oxidation. On the other hand, composted BSG material did not perform well to oxidize CH_4. Therefore it is not a good option as biocover material. The Response Surface Modelling using the Design Expert Software was very useful in designing the experiments needed. In conclusion, BSG can be utilized as a biocover material for CH_4 oxidation.