RESEARCH ARTICLE

# Optimizing the Biochemical Methane Potential (BMP) of Food Waste

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**Abstract:** Recent advances in anaerobic digestion has resulted in expansion of sustainable methods for use of waste as energy resources. Conventional methods prove to be uneconomical and environmentally impractical. Moreover, the microbial consortia in anaerobic digestion are temperature dependent and therefore requires investigations on temperature optimization. Therefore, the recent experimental study is being undertaken with the objective in order to assess the effect of temperature on anaerobic biodegradation of food wasted from a hostel campus. The effect of temperature on methane generation rate has also been investigated. The anaerobic digestion study under psychrophilic, mesophilic and thermophilic temperature conditions has been carried out and compared in order to assess the optimum methane production conditions. All the experimental study for anaerobic digestion of food waste has been carried out at optimum F/M (food to mass) ratio of 0.75. The cumulative highest methane production is observed to be 33, 50 and 65 mL of $CH_4$ in reactor R1, R2 and R3 with initial food waste COD dosage of 100, 150 and 200 mg, respectively under mesophilic temperature conditions. The highest biochemical methane potential (BMP) value of 0.94, 0.95 and 0.93 $gCH_4$-COD/$gCOD_{fed}$ in reactor R1, R2 and R3 respectively, under mesophilic temperature conditions. It been observed that for maximum methane generation rate constant of 0.62 $d^{-1}$ were observed under thermophilic conditions thus has to be highly accelerative process but overall conversion of organic matter to methane is less as compared to mesophilic temperature conditions, this is because free ammonia concentration increases with increasing temperature, by influencing the equilibrium. However, mesophilic conditions provide a more stable environment for the anaerobic digestion process. This may be due to the fact that temperature fluctuations can disrupt the microbial activity and slow down the process, but mesophilic conditions provide a stable environment for the microorganisms to thrive. Therefore, the mesophilic temperature range provides a balance between high reaction rates, stability, and cost-effectiveness, making it the optimal temperature range for anaerobic digestion of food waste. The obtained results in present study will be helpful in implementing on full-scale anaerobic solid waste digesters for enhancing the methane generation under mesophilic temperature conditions with high organic matter removal. Also, under thermophilic conditions the energy requirement for heating proves to be uneconomical.
**Keywords:** Anaerobic digestion, food to mass ratio, methane, food waste, temperature

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## 1 Introduction

In the present scenario increasing in demands of energy necessitates the generation of supplementary power by all power sectors either by conventional method or non-conventional method. However, some of the conventional methods are not eco-friendly and contributes to environmental degradation. Therefore, it is obligatory to generate energy using environment-friendly methods also known as the renewable energy sources. In India utmost part of the economy depends upon the agriculture and its related businesses like agro industries and dairy industries. Therefore, a huge potential of renewable energy exists in waste produced from agriculture or its related activities. However, the processes used for energy production generally depends on certain governing factors. In case of anaerobic digestion (AD) process pH and temperature is a major governing factor. The treatment of waste carried out in anaerobic digesters generally operated under mesophilic temperature conditions of around 30-40°C but sometimes under such digester are operated even under thermophilic temperature conditions of around 50-60°C or even hyper-thermophilic conditions of 65-75°C (Kim et al., 2017).

The total energy demand in India is approximately 1,048,672 MW. However, total renewable energy generation considering off grid and on grid is 35,493 MW approximately. It is around 13% of the total energy generation till Feb 2015. Therefore, in order to fulfil this emerging energy demand and due to inadequate stock of non-renewable form of energy sources, generation of energy from renewable sources is emerging in the present scenario. In India the energy consumption in residential areas mainly depends on the fuel wood, kerosene, liquefied petroleum gas (LPG), compressed natural gas (CNG) and electricity. In rural sector wood derived fuel is the largest source of energy for cooking purpose. However, biogas generated from agricultural residue is a best alternative to overcome this problem both in rural as well as in urban areas. A study being carried out by Food and Agriculture Organization (FAO), United Nations and Pan American Health Organization (PAHO) has been carried out on solid waste during agricultural production around the globe. It has been reported that around 1.3 billion tons of food is being lost per year in the sectors of agricultural production, post-harvest, and processing. This leads to wastages in retail sales and final consumption through the food supply chain for human consumption. In Latin America and Caribbean in 2016, about 127 million tons of food is estimated to be wasted in numerous agricultural linked activities (Blasius et al., 2020).

Biomass is rich renewable source, which is easily available and can be transformed to valuable form of biogas as energy resource. The food waste in urban sector is generated in small amount as compared to the rural sector. Now a days, biomass and municipal solid waste are frequently utilized for the generation of biogas. Biogas generation is very advantageous for cooking and electricity purpose due to increasing cost of LPG and electricity. This food waste is an essential component for biogas generation. In recent years, utilization of LPG and electricity has increased to a great extent for the purpose of cooking food and other uses (Parker, 2005). Thus, the enhanced usage of LPG and electricity due to ease of availability has led to its enhancement of cost.

A new trend of production of biogas from wood has initiated in the recent years. This leads to the generation of methane when the availability as food waste is in larger amount. Creating awareness among the rural sector people regarding the utilization of the biogas is an intermediate step towards enhancement of knowledge of the people of rural areas (Ward et al., 2008). This intermediate step plays a big role in money saving and in maintenance of a sustained and clean environment. Biogas is very advantageous for the rural sector because raw material is easily available in rural areas. The residue of biogas also familiar as slurry are very useful for the agriculture because it enhances the productivity of crop and leads to production of healthy organic food (Banks et al., 2011). Although there is abundant availability of biomass in India, only small percentage of biomass is available for generation of useful energy from the biogas due to lack of technology and awareness. Therefore, technical education and awareness is a necessary step for proper utilization of biomass for generation of useful energy. Biogas and slurry are the end product of the organic cycle. The characterization of the food waste is affected by various factors including changing climatic condition, collection frequency and technological variations (Lisboa and Lansing, 2013).

Yang et al. (2004) in a study discussed about the anaerobic digestion technology and reported that the biogas generation during biodegradation of organic matter led to production of energy rich biogas. It can be best alternative for the replacement of fossil energy sources that are very limited now (Yang et al., 2004; Khalid et al., 2011; Gunaseelan, 2004; Rao and Singh, 2004). Various investigators confirms that usually the composition of biogas includes 36-41% $CO_2$, 17% $N_2$ , 48-65% $CH_4$ and >1% $O_2$ (Ward et al., 2008). In anaerobic digestion the first step is when organic matter which is complex in nature and contains lipids, proteins and carbohydrates is transformed into simpler molecules such as amino acids, sugars and fatty acids. The process is generally known as Hydrolysis. The second step is an acidogenesis process in which soluble organic molecule is converted in to volatile fatty acids (VFA). In acetogenesis process, these fatty acids are converted into acetic acid. Methanogenesis is final step of the process that involves conversion of acetic acid to biogas (Dioha et al., 2013; Elbeshbishy et al., 2012; Zhu and Jha, 2013; Luna-delRisco et al., 2011; Tanimu et al., 2014). Budiyono et al. (2013) in a study concluded that the anaerobic digestion depends on pH, temperature, mixing, moisture, and total solids content, temperature that generally influences the degradation of food waste.

Another study reported the calorific value of biogas generated from the food waste to be approximately 26-30 J/m$^3$ (Mohan and Jagadeesan, 2013). Researchers have determined the kinetic parameters by conducting batch experiments for examining the effects of substrate concentration on the methanogenesis (Ofoefule et al., 2010). Pandyaswargo et al. (2015) analysed anaerobic process through seven degradation sub process to produce biogas from the anaerobic raw material. Therefore, seeing the above cited practicalities in view an experimental study was being setup with the aim to assess the biochemical methane potential (BMP) in biodegradation of food waste anaerobically.

# 2 Materials and Methods

## 2.1 Sample collection and characterization

For the experimental setup, all the chemicals used for preparation of media, nutrients and chemical analysis were of analytical grade. The food waste samples utilized to evaluate the temperature effect on methane production were collected from student hostel of the campus located in Netaji University of Technology, Dwarka, New Delhi, India. The collected food waste samples were oven dried at 70°C for 24 hours in order to eradicate the water content. After drying the food waste was grinded and sieved to prepare a homogeneous mixture of the sample. The seed sludge utilized as inoculum in the experimental work was procured from a 72 MLD real scale anaerobic UASB (Up-flow Anaerobic Sludge Blanket) technology-based wastewater treatment plant located at Indirapurm, District Ghaziabad, Uttar Pradesh, India. Initially prior start of each experiment, the food waste (sample) characteristics including chemical oxygen demand (COD), total organic compound (TOC), volatile suspended solids (VSS), pH, total phosphorus, total kjeldahl nitrogen (TKN) and moisture content were determined.

All the parameters in present study were analysed as per the standard methods prescribed in soil & solid waste analysis: as per standard methods for the examination of water and wastewater, APHA 2017 (Baird et al., 2017). COD determination was carried out using closed reflux colorimetric UV-VIS spectrophotometric method. VSS determination done by gravimetric method using oven and muffle furnace. The Walkley and Black-recommended titration method was employed for TOC determination. Phosphorus and TKN were determined using digestion and titrimetric method prescribed in solid waste manual. For determination of N and P, the food waste as biomass was digested. However, substrate/sample and inoculum moisture content determination were being carried out by using gravimetric method. Defined media and concentrated stock solutions with nutrients used in each batch bioassay preparation was carried out as per methodology prescribed by (Hussain et al., 2009). The prepared defined media stored in a 2-L glass bottles afterwards purging the $N_2$ gas through the media and sealed in order to avoid the oxygen interfering.

## 2.2 Batch test study

Serum bottle technique used to carry out the experimental batch test study is depicted by Figure 1. Present investigation has been carried out using serum bottle technique using 500 mL bottle with working volume of 400 mL. Before initiation of the experiment, samples along with Inoculums were well mixed to maintain the anaerobic condition by purging oxygen gas in each reactor. The present experimental batch test study has been carried out to assess the optimum F/M ratio on anaerobic biodegradability of food waste.

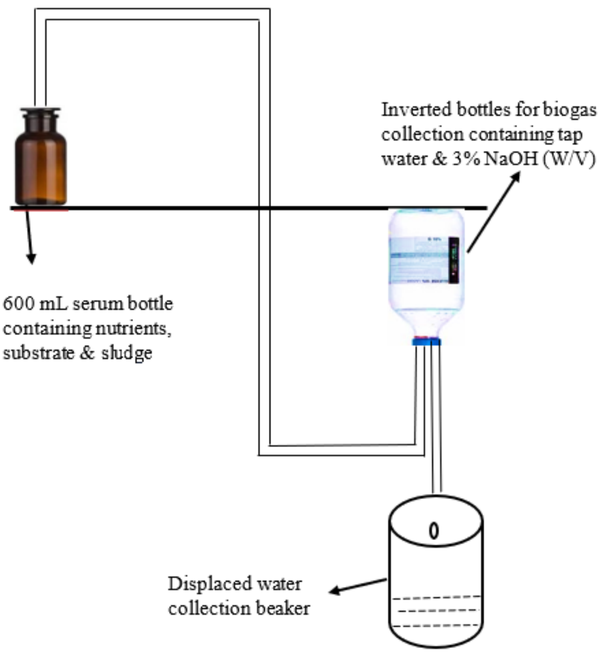


**Figure 1.** Experimental setup for batch test study.

In present experimental study, all the analysis was carried out in triplicate sets, and average of close two values has been utilized for assessment of results. The volume of methane generated after blank corrections is converted to methane COD values and results are reported accordingly. The food waste and inoculum (seed sludge) in required concentrations were added to serum bottles flushed with 70% $N_2$ and 30% $CO_2$. Thereafter the batch bottles were caped using rubber stopper and sealed airtight. In order to maintain appropriate anaerobic conditions, the total working volume including sample, nutrients defined media and seed inoculum was kept 400 mL.

The methane collection was being carried out using water displacement method using inverted serum bottles filled with water containing 5% of NaOH for absorbing $CO_2$. Also, the empty beakers were placed below the inverted bottles to collect the displaced water as shown through Figure 1. In order to crosscheck the daily production of methane volume was also measured by withdrawing the gas from serum bottle using glass syringes of 5-30 mL volume equipped with 20-gauge needles. All the experimental study has been carried out at an optimum F/M ratio of 0.75 (Negi et al., 2018). Cumulative methane production in overall study was monitored on daily basis. The obtained experimental data has been used to evaluate the value of methane generation rate constant (k).

It is assumed that the methane conversion rate of the degraded biomass depends on the total amount of organic matter yet to be degraded. The methane generation rate constant follows the kinetics of first order rate constant equation. It is also assumed that the methane production rate generally depends on the rate at which organic matter degrades. It may be defined by the equation (Equation 1) below:

$$\mathrm{Y}_t = \mathrm{Y}_o\ (1\text{-}\mathrm{e}^{-kt}) \qquad (1)$$

Where, $Y_o$ = Maximum cumulative methane yield (L), $Y_t$ = Cumulative methane yield (L) at time (t), k = methane generation rate constant expressed as days$^{-1}$ ($CH_4$), t = Time in days (d).

The methane generation rate constant (k) has been assessed by using the above-mentioned equation (Equation 1). Quasi-Newton algorithm has been used to evaluate the k value by using best curve fitting method. The sum of squared differences between the experimental and calculated values is generally minimized by the algorithm to estimate model parameter values. Thereafter, the nonlinear optimization function has been employed in the function using the $K_y$-plot software and based on the maximum methane yield value the k values has been computed and presented.

# 3 Result and Discussion

## 3.1 Characteristics of food waste and inoculum

In present batch test study, food waste digestion has been carried out anaerobically under varying temperature conditions.

The temperature effect on anaerobic digestion of food waste (substrate) has been conducted under mesophilic (35±2°C), thermophilic (55±2°C) and psychrophilic (15±2°C) temperature conditions. The methane production was measured daily and the cumulative methane addition being used for calculating the $CH_4$ generation rate constant. Prior to experimental study physico-chemical parameters of the collected samples has been carried out and the obtained results are summarized in Table 1. The moisture content in food waste is estimated to be 71% with a pH value of 6.85 thus indicating towards neutral side. The COD concentration of 9.9 g/g with TOC of 65% indicates the suitability of the food waste sample towards biological degradation. The volatile suspended solids concentration of 0.72 g/g thus indicates the organic matter content in the sample. However, the nitrogen concentration in terms of total kjeldahl nitrogen (TKN) along with total phosphorus concentration is observed to be 2.8 mg/g and 6.9 mg/g respectively. The values thus indicating the enrichment of these two major nutrients in the food waste.

**Table 1.** Physico-chemical characteristics of food waste and inoculum

| S. No. | Parameters | Substrate (Food waste) | Inoculum (Food waste) |
|---|---|---|---|
| 1 | Moisture Content (%) | 71 | - |
| 2 | pH | 6.85 | 7.48 |
| 3 | Total Phosphorus (mg/g) | 6.9 | 0.72 |
| 4 | Chemical Oxygen Demand (g/g) | 9.3 | 8.5 |
| 5 | Total Organic Carbon (%) | 65 | 47 |
| 6 | Volatile Suspended Solids (g/g) | 0.72 | 0.65 |
| 7 | Total Kjehldal Nitrogen (mg/g) | 2.8 | 2.1 |

The characteristics of the sludge for seeding has been determined in the present study as inoculum has also been carried out prior to each experiment. It has been observed that the sludge sample with pH value of 7.48 is towards neutral side. The volatile suspended solids in the sludge has been found to be 0.65 g/g thus signifying it towards high microbial concentration. However, the nitrogen concentration in terms of TKN along with total phosphorus concentration has been found to be 2.1 mg/g and 7.2 mg/g respectively. This indicates the plenty of nitrogen and phosphorus in the microbial cells as major nutrients. Based to the physico-chemical characteristics as mentioned in Table 1, the experimental setup was planned at F/M ratio of 0.75 as optimum value. In present batch test study triplicate sets of serum batch bottles were laden with required concentration of food waste (sole substrate) and sludge as inoculum to maintain an optimum F/M ratio of 0.75. Each set of all the batch reactors were kept in the incubator under psychrophilic 15±2°C, mesophilic 35±2°C and thermophilic 55±2°C temperature conditions. The cumulative methane production values are measured and expressed in mL of $CH_4$ at standard temperature and pressure (STP).

## 3.2 Methane Production

After the blank corrections in all the obtained values, the cumulative methane production at F/M ratio of 0.75 was monitored for a period 30 days or till the methane generation ceased. The obtained values of cumulative methane generation as depicted through Figure 1-3 indicates the exponential growth curves being drawn after subtracting the initial lag phase period of 2-3 days. The observed lag period thus indicates the transformation in microenvironment and acclimatization phase of which initial step seems to be slow. However, conversion of acids to methane in anaerobic biodegradation is considered as rate limiting step. The delay in gas production results in lag phase is an indicator of delay in biotransformation activity. This may be due to the fact that in a multistage successive bioconversion of organic matter to methane with initial step to be slower process trailed by accelerative conversion of intermediate products to methane. The degradability of food waste has been computed from the obtained results and expressed in terms of methane generation rate constant (k, $d^{-1}$). Similarly, the biochemical methane potential is another parameter generally used to portray the conversion of $COD_{fed}$ to $CH_4$-COD over a period of time.

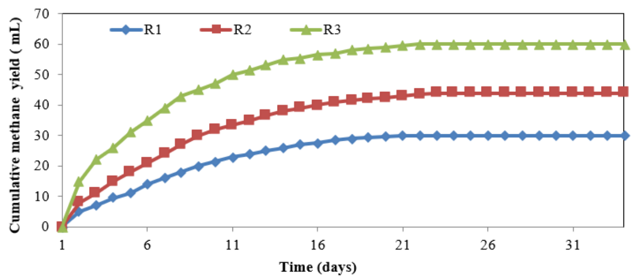


**Figure 2.** Cumulative methane ($CH_4$) under mesophilic temperature conditions.

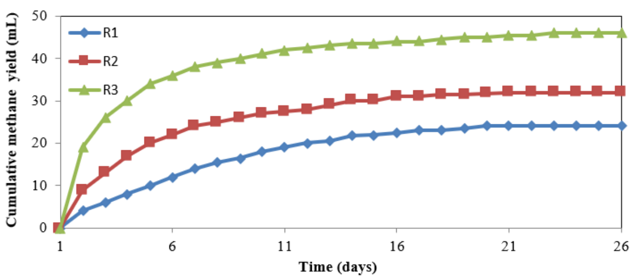


**Figure 3.** Cumulative methane ($CH_4$) under thermophilic temperature conditions.

In present study it has been observed that methane generation started after a lag period 2 to 5 days of the experiment carried out under mesophilic conditions. The methane generation was monitored daily till the gas production ceased completely at 33 days period in all the reactors as shown through Figure 2. The data summarized in Table 2 and Fig-

**Table 2.** Methane yield and methane generation rate constant under varying temperature conditions

| Reactors | Batch Reactor Type | Substrate added (g) | Maximum Methane produced (mL) | Methane generation Rate constant, K ($d^{-1}$) | BMP ($gCH_4COD/gCOD_{fed}$) | Temperature (°C) |
|---|---|---|---|---|---|---|
| Reactor 1 | R1 | 0.1 | 21 | 0.12 | 0.6 | 15 |
| Reactor 2 | R2 | 0.15 | 30 | 0.1 | 0.57 | |
| Reactor 3 | R3 | 0.2 | 37 | 0.11 | 0.53 | |
| Reactor 1 | R1 | 0.1 | 33 | 0.32 | 0.94 | 35 |
| Reactor 2 | R2 | 0.15 | 50 | 0.33 | 0.95 | |
| Reactor 3 | R3 | 0.2 | 65 | 0.37 | 0.93 | |
| Reactor 1 | R1 | 0.1 | 30 | 0.34 | 0.86 | 55 |
| Reactor 2 | R2 | 0.15 | 37 | 0.42 | 0.7 | |
| Reactor 3 | R3 | 0.2 | 52 | 0.62 | 0.74 | |

ure 2 indicates that the cumulative methane production in all the reactors in anaerobic biodegradation of food waste has been found to be 33, 50 and 65mL of $CH_4$ in reactor R1, R2 and R3 with COD dosage of 100, 150 and 200 mg respectively. However, under thermophilic temperature conditions at 55±2°C, the methane generation started within 2 days duration of the experimental study. The methane generation is observed to be accelerative and ceased on $26^{th}$ day of the experiment as depicted through Figure 3. Perusal of the data summarized in Table 2 indicates the maximum methane production of 30, 37, 52 mL has been observed in reactor R1, R2 and R3 with COD dosage of 100, 150 and 200 mg, respectively.

The present batch test study has been carried out under psychrophilic conditions at15±2°C also. The lag phase of more than 7 days indicates a delay in methane generation under psychrophilic temperature conditions. Higher lag phase at lower temperature thus indicates the change in microenvironment thus delaying the initial step. The methane production is observed to be slow and ceased on $53^{rd}$ day of the experiment as shown through Figure 4. However, data from Table 2 designates the maximum methane production of 21, 30, 37 mL has been assessed in reactor R1, R2 and R3 with COD dosage of 100, 150 and 200 mg, respectively.

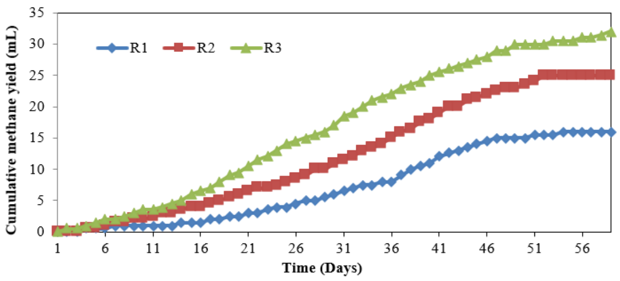


**Figure 4.** Cumulative methane ($CH_4$) under Psychrophilic temperature conditions.

## 3.3 Biochemical methane potential (BMP) and Methane generation rate constant (k)

BMP is a parameter used to measure the biodegradability of any substrate and is determined by monitoring the cumulative methane production of such a sample that is incubated anaerobically under chemical defined medium conditions (Negi et al., 2018). It is represented as mL of $CH_4$ at STP converted to $gCH_4$-COD/gCOD$_{fed}$.

Under mesophilic temperature conditions and deducting lag phase of 2-5 days the maximum methane production of 33, 50 and 65 mL in reactor R1, R2 and R3 respectively. The maximum substrate degradation as confirmed with gas ceasing on 23, 29 and 33 days of the experiment. Perusal of the data summarized in Table 2 indicates the BMP value of 0.94, 0.95 and 0.93 $gCH_4$-COD/gCOD$_{fed}$ in reactor R1, R2 and R3, respectively. The maximum methane produced after the termination of experimental study under mesophilic conditions signifies the maximum substrate conversion value of 95% of its theoretical or stoichiometric methane produced value (Table 2). While under thermophilic temperature conditions the BMP values of 0.86, 0.70 and 0.74 $gCH_4$-COD/gCOD$_{fed}$ has been assessed in reactor R1, R2 and R3 respectively. This appears to be lesser than the values obtained under mesophilic conditions. However, under psychrophilic temperature conditions the BMP values of 0.60, 0.57 and 0.53 $gCH_4$-COD/gCOD$_{fed}$ has been assessed in reactor R1, R2 and R3, respectively. Therefore, the study indicates that the conversion of organic matter in a waste to $CH_4$ production appears to be limited and is temperature dependent. In other words, temperature <35°C or >35°C adversely affects or reduces BMP of a biodegradable waste. Therefore, from present study it is confirmed that mesophilic temperature condition (35±2°C) is optimal for anaerobic biodegradation of food waste. The calculated BMP value is analogous to the BMP value of 0.97 $gCH_4$-COD/gCOD$_{fed}$ in phenolic wastewater (Hussain et al., 2010).

Methane generation rate constant in terms of k has also been evaluated and the results are summarized in Table 2. The correlation between experimental data and computed values under different temperature conditions for different samples is shown through Figure 5. The data presented in Table 2 reveals that the k values varies between 0.10 - 0.62 $d^{-1}$ in all the experiments.

However, under mesophilic conditions the computed k values is found to be in between the range of 0.32, 0.33 and 0.37 $d^{-1}$ in reactor R1, R2 and R3 respectively. However, the low-

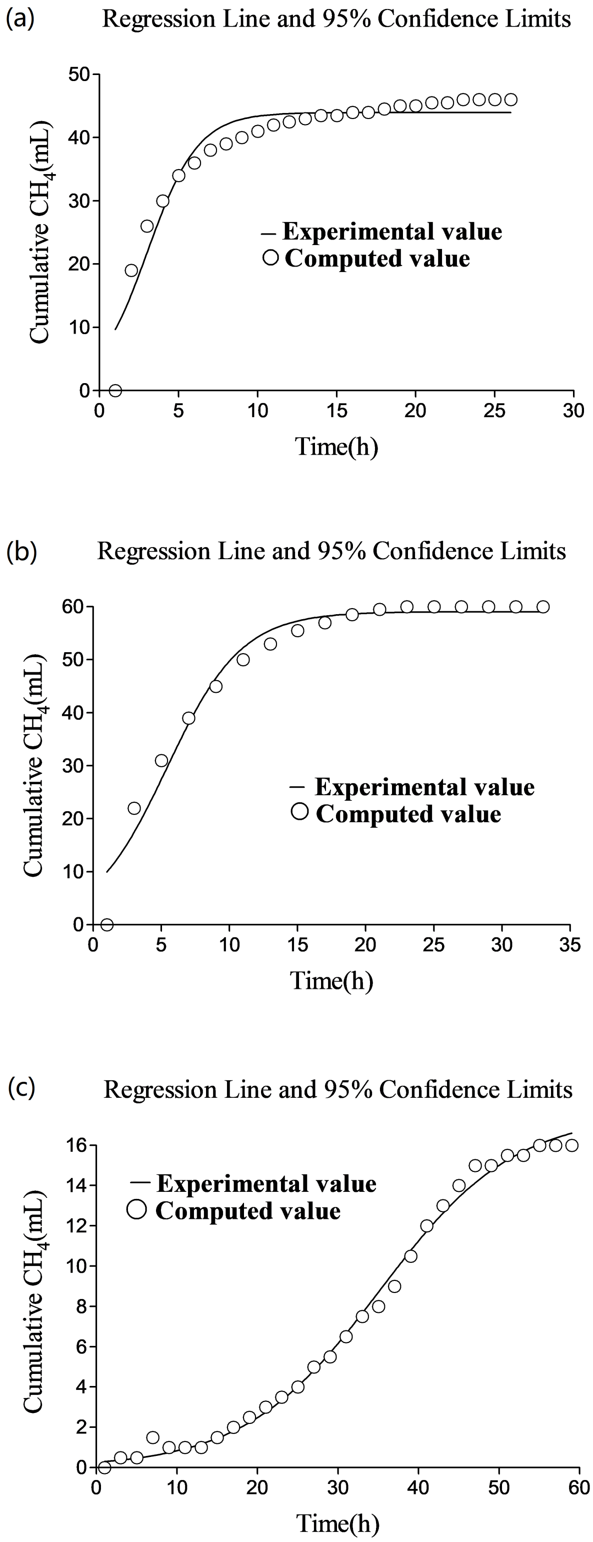


**Figure 5.** Comparison of experimental and model computed maximum k value under (a) Thermophilic (b) Mesophilic (c) Psychrophilic temperature conditions using $K_y$ plot.

est k value of 0.12, 0.10 and 0.11 $d^{-1}$ has been assessed in reactor R1, R2 and R3 under psychrophilic conditions. Also, under thermophilic conditions the rate constant k value lies of 0.34, 0.42 and 0.62 $d^{-1}$ in reactor R1, R2, R3 respectively. It has been observed that for maximum methane generation rate constant of 0.62 $d^{-1}$ has been observed under thermophilic conditions thus appears to be highly accelerative process but overall conversion of organic matter to methane is less as compared to mesophilic temperature conditions. The lowest k value of 0.10 $d^{-1}$ has been observed under psychrophilic conditions. However, under mesophilic temperature conditions the highest k value of 0.37 $d^{-1}$ has been assessed but overall conversion of organic matter to methane has been found to be highest as compared to thermophilic temperature conditions. This also designates the substantial effect of temperature on methane generation rate constant (k).The obtained k value in present study can be well compared with the k values reported in the literature for the anaerobic degradation of soluble wastewater including complex synthetic sewage (Hussain et al., 2009). Thus, it confirms that though under temperature-controlled conditions, the biodegradation of organic matter is accelerative under thermophilic conditions but overall biotransformation of organic matter in terms of COD to methane is higher under mesophilic temperature conditions.

Therefore, from present study it is recommended that real scale waste treatment plant comprising of anaerobic digesters or biogas reactors when run under mesophilic temperature conditions will be helpful in improving the efficiency of the biogas reactor. The suggested scheme will be helpful in enhancement of methane production in a biogas reactor.

## 4 Conclusion

From the present study it is concluded that in anaerobic biodegradation of food waste the cumulative methane generation profiles follows exponential growth curve. The lag phase of more than 7 days indicates a delay in methane generation under psychrophilic temperature conditions. The maximum methane produced after the termination of experimental study under mesophilic conditions signifies the maximum conversion of 95% of theoretical or stoichiometric methane converted from food waste as a substrate. Thus, it confirms that though under temperature-controlled conditions, the biodegradation of organic matter is accelerative under thermophilic conditions but overall conversion of organic matter in terms of COD to methane is higher under mesophilic temperature conditions. It has been observed that the maximum methane generation rate constant of 0.62 $d^{-1}$ has been observed under thermophilic conditions thus appears to be highly accelerative process but overall conversion of organic matter to methane is less as compared to mesophilic temperature conditions. Therefore, it is noteworthy that anaerobic biodegradation of food waste in real scale systems should be carried out under mesophilic temperature conditions for optimum methane production and maximum organic matter removal.

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## Authors Contribution

Athar Hussain and Gaurav Saini: Design & supervision of study, data analysis, manuscript writing and editing. Manjeeta Priyadarshi and Shivani Patel: Sample collection, experimental work, data analysis and writing initial manuscript draft.

## Data Availability

All data generated or analyzed during this study is included in the article.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Ethical Approval

This article does not contain any studies with human participants or animals performed by the authors involved.

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