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# Biogas Generation in a Vegetable Waste Anaerobic Digester: An Analytical Approach

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## Abstract

*Mixture of vegetable wastes was an-aerobically digested in a 500 ml capacity lab scale batch reactors. Vegetable wastes having near similar pH and moisture content have been chosen so that overall pH and total solids content do not vary significantly in the feed composition for the study. Carrot, beans and brinjal having pH 5.4, 5.8 and 5.7 and moisture content 89.8%, 90.29% and 89.4% respectively were chosen for the study. These wastes contain predominantly carbohydrates and less protein and fat. Studies were carried out by preparing the feed consisting of carrot, beans and brinjal in different proportions to obtain organic load ranging from 0.06gm VS to 0.47 gm VS. The performance of the reactors was evaluated by estimating destruction of total and volatile Solids and by monitoring daily gas production. Mean methane production rate were determined at different organic loading range. Predictive models for analyzing the performance of the batch reactor and for determining cumulative biogas production for a given organic loading have been developed. The kinetics of the process has been studied using first order rate equation and reported in the paper.*

**Keywords**: Anaerobic digestion, fruit and vegetable wastes, biogas, batch reactor.

## Introduction

One of the burning problems faced by the world today is management of all types of wastes and energy crisis. Rapid growth of population and uncontrolled and unmonitored urbanization has created serious problems of energy requirement and solid waste disposal. Vegetable market wastes contribute to a great amount of pollution; hence, there has been a strong need for appropriate vegetable waste management systems. Vegetable wastes that comprise of high fraction of putrecible organic matter cause serious environmental and health risks.

Biological conversion of biomass to methane has received increasing attention in recent years[1]. There are many technologies such as incineration and refuse derived fuel (RDF) etc., for producing energy from solid wastes. Among them anaerobic digestion has become a promising technology particularly for recovery of energy from organic fraction of solid wastes. Many research works are being carried out for treating various types of organic solid wastes using anaerobic digestion process. It has become a major focus of interest in waste management throughout the world. Anaerobic Digestion is potential environment friendly technique produce energy in the form of biogas [2, 3] and residue which can be used as soil conditioner[4-6].

It is known that organic waste materials such as vegetables contain adequate quantity of nutrients essential for the growth and metabolism of anaerobic bacteria in biogas production[7]. India produces 150 million tones of fruits and vegetables and generates 50 million tones of wastes per annum[8], Therefore it become necessary to develop appropriate waste treatment technology for vegetable wastes to minimize green house gas emission.

Several studies have been reported on the bioconversion of biomass by different researchers. For example, the anaerobic digestion of solid refuses like municipal solid wastes[9-11], Barcelona's central food market organic wastes[3], canteen wastes[12], market wastes[13], water hyacinth[14], sugar mill press mud waste[15] and fruit and vegetable processing wastes[16-18] have been reported. The process of digestion and production of biogas depends on the composition of feedstock and the fermentation products of the vegetable wastes. Most of the vegetables are cultivated seasonally. Accordingly the type of wastes generated varies considerably in quantity and composition. Therefore it is necessary to study the effects of variation in the composition of vegetable wastes on the performance of anaerobic digestion process.

The main objective of this research is to employ anaerobic digestion process as a sustainable technology for digesting the vegetable wastes, produced in large amounts during harvesting, handling, transportation, storage, marketing and processing, and to provide the renewable source of energy as well as to reduce the potential green house gas emission. The specific objectives are (i) To optimize the methane gas evolution from the vegetable waste. (ii) To analyze the operational parameters, such as characteristics of substrates, organic loading and hydraulic retention time, for the stability of anaerobic digestion system. (iii) To get an understanding of the anaerobic digestion of the vegetable wastes under ambient temperature conditions by conducting a lab scale study and hence to investigate the biogas yield and the kinetics of anaerobic digestion of vegetable waste fed.

Vegetable wastes largely contain carbohydrates. Proteins and fats are present relatively in low concentrations. Anaerobic digestion of carbohydrates, fat and proteins are expected to yield 886l ml, 1535l ml and 587l ml of biogas per kgVS$_d$ and generate biogas containing 50%, 70% and 84% of methane respectively[19,20]. Keeping in view the biogas yield reported for the carbohydrates, fat and proteins, vegetable wastes, namely, Carrot, Beans and Brinjal, which have near similar pH, moisture content and carbohydrates, shown in table.1, were chosen as model components to study the performance of mixture of vegetable wastes in the anaerobic digestion process.

**Table -1**
**Characteristics s of the vegetables**

| Sl.No | Component | Carrot | Beans | Brinjal |
|---|---|---|---|---|
| 1 | pH | 5.4 | 5.8 | 5.7 |
| 2 | Moisture Content ** | 89.9 | 90.29 | 89.4 |
| 3 | Carbohydrate * | 5.6 | 4.1 | 5.7 |
| 4 | Fat* | 0.2 | 0.2 | 0.19 |
| 5 | Protein* | 0.6 | 1.9 | 1.01 |

Except pH all are given in gm, * Amount present in 100gm, ** Moisture content is given in percentage

## Material and Methods

**Experimental Procedure:** Batch studies were carried out in nine reactors of 500 ml Capacity (R1, R2, R3, R4, R5, R6, R7, R8 and R9). The reactors were made of borosilicate glass. The effective volume of the reactors was maintained at 300ml. The reactor was provided with suitable arrangements for feeding, gas collection and draining of residues. The reactor was operated by draw and fill method. Experiments were carried out in the mesophilic temperature range. Each reactor was initially inoculated with 150 ml of sludge, obtained from an active mesophilic digester of vegetable market waste Biomethanation plant at Koyembedu, Chennai, India, and diluted to 300ml working volume. The characteristics of inoculums and the diluted sludge in the reactor are given in the table 2.

**Table–2**
**The characteristics of the inoculum and diluted sludge**

| Parameter | Inoculum | Diluted sludge in the reactor |
|---|---|---|
| Total solids (TS) | 13.90 | 6.03 - 6.7 |
| Volatile solids (VS) | 43.82 | 47.93 - 49.3 |
| pH | 6. 5 | 6.15 - 7. 26 |

Except pH all are in percentage.

The feedstock selected for the experiment was grinded mixture of three vegetables, namely, carrot, beans and brinjal kept at 4$^o$C until used. Each reactor was charged separately with a quantity of substrate containing 0.06gmVS(R1), 0.09gmVS(R2), 0.13gmVS(R3), 0.15gmVS(R4), 0.19gmVS(R5), 0.26gmVS(R6), 0.34gmVS(R7), 0.43gmVS(R8) and 0.47gmVS(R9), after removing equivalent amount of sludge from the reactor. Daily biogas production was measured by water displacement method. The volume of water displaced from the bottle was equivalent to the volume of gas generated. The rectors were mixed manually by means of shaking and swirling once in a day. The quantity and composition of the feedstock added for the different organic loading is given in the table 3. The pH of the feed mixture is ranging from 4.0 to 5.3, total solids is from 7.46 % to 9.83 % and total volatile solids is 89.66% to 95.01%.

**Analytical methods:** pH was measured using digital pH meter. Total solids (TS), volatile solids (VS) were estimated according to the procedures recommended in accordance with the procedures prescribed in IS 9234 – 1979, IS 10158 – 1982 and standard methods of examination of water and waste water (APHA –AWWA 1992) as appropriate.

**Table-3**
**The composition of the feedstock added**

| Substrate loading gmVS | Amount of feed added (g) | %TS of Feed Mix | %VS of Feed Mix | pH of Feed Mix |
|---|---|---|---|---|
| 0.06 | 18 | 9.8 | 94.57 | 4.8 |
| 0.09 | 27 | 7.46 | 95 | 4.8 |
| 0.13 | 39 | 9.57 | 94.64 | 4.7 |
| 0.15 | 45 | 9.5 | 94 | 5.3 |
| 0.19 | 57 | 9.57 | 94.64 | 4.7 |
| 0.26 | 78 | 7.46 | 95 | 4.8 |
| 0.34 | 102 | 9.51 | 95.01 | 4.0 |
| 0.43 | 129 | 9.83 | 92.83 | 4.1 |
| 0.47 | 141 | 9.21 | 89.66 | 5.2 |

## Results and Discussion

**Effect of pH, TS and VS on gas production:** pH, %TS reduction, %VS reduction and cumulative gas production at the end of the cycle, mean production of methane (R/Ri), relative substrate concentration (S/Si) and kinetic constants for the different organic loading are given table 4.

In an anaerobic system, the acetogenic bacteria convert organic matter to organic acids, possibly decreasing the pH, reducing the methane production rate unless the acids were quickly consumed by the methanogens. pH in the range of 6.8 to 7.4 should be maintained in the anaerobic digestion process which is optimum range for methanogens growth[21]. pH of the reactor residue after the completion of cycle is ranging from 3.9 to 8.6, which was slightly above optimal pH for the substrate concentration 0.06 to 0.26gmVS and below optimal pH for the substrate concentration of 0.34 to 0.47gmVS. From table 4 it is seen that the total biogas yield is not totally affected by the quantity of substrate loaded but by the percentage of total solids digested.

Variation of cumulative biogas production and daily biogas production as a function of time (days) is shown in figure 1 and 2 for different substrate loading. It was observed that degradation of substrate started almost immediately for all the substrate concentrations. The maximum gas production was observed during the first 5 – 10 days.

The mean methane production, R (based on digester volume) was calculated after a preset time of 9 days (time in which most of the substrate had been used up). The plot of R/Ri versus S/Si, figure 3, was made to study the effect of substrate concentration on gas production, where Si is the lowest substrate concentration used in the study and Ri is the corresponding mean gas production. It shows a maximum for the substrate concentration 0.26gm/VS after which the relative rate of gas production decreased markedly as observed for sugar-mill-mud waste[15]. This suggests that the inhibition process occurs for this substrate at concentrations above 0.26 gmVS.

**Analysis of the predictive models:** The daily and cumulative biogas generation monitored for different substrate loadings were used for developing predictive models for the generation of biogas for different substrate loading for various retention time[22]. Graphs representing the relationship between retention time and the biogas yield for various substrates loading were plotted. After plotting the graphs, each of these graphs have been tested with the trend lines, of the various functions, which include linear, logarithmic polynomial, power, exponential and moving averages. The regression/trend models that give the highest level of correlation coefficient between the type of regression model and the data generated from the experiments were determined. After carrying out this analysis, a comparative study of $R^2$ values was observed. The highest values of $R^2$ were chosen as the best fit to the experimental data.

After plotting the graphs of biogas yield versus retention time, curve fitting was carried out to determine what predictive model best illustrates the experimental results. The graphs were tested with linear and polynomial equations. In these, the equations that describe these functions were fitted to the experimental data and the error measured. The equations derived from figure.1 for total biogas production are given in table.5.

The best fit was observed only in the case of polynomial correlation with error less than 10% compared to linear one. So, polynomial function seemed to be more reliable in predicting gas production in anaerobic digestion of vegetable wastes.

**Table-4**
**pH, TS% reduction, VS% reduction, R/Ri values, S/Si values and kinetic constant for the reactors operated with different substrate concentration**

| Amount of feed added (g) | Substrate loading gmVS | pH | Cumulative gas produced ml | % reduction of TS | % reduction of VS | R/Ri | S/Si | k (time$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| 18 | 0.06 | 8 | 788 | 60 | 77.4 | 1 | 1 | 0.13 |
| 27 | 0.09 | 7.87 | 1715 | 63.9 | 85.4 | 2.172 | 1.5 | 0.15 |
| 39 | 0.13 | 8.3 | 2685 | 80.6 | 86.7 | 3.695 | 2.167 | 0.27 |
| 45 | 0.15 | 8.6 | 1967 | 78.4 | 86.9 | 2.7 | 2.5 | 0.22 |
| 57 | 0.19 | 7.9 | 3368 | 83.2 | 86.3 | 4.452 | 3.167 | 0.22 |
| 78 | 0.26 | 8.09 | 3764 | 77.8 | 86.3 | 4.097 | 4.333 | 0.22 |
| 102 | 0.34 | 6.2 | 825 | 50.3 | 69.6 | 2.0 | 5.7 | 0.17 |
| 129 | 0.43 | 5.1 | 669 | 40.9 | 51.6 | 0.3 | 7.2 | 0.040 |
| 141 | 0.47 | 3.81 | 194 | 27.1 | 35.9 | 0.1 | 7.8 | 0.058 |

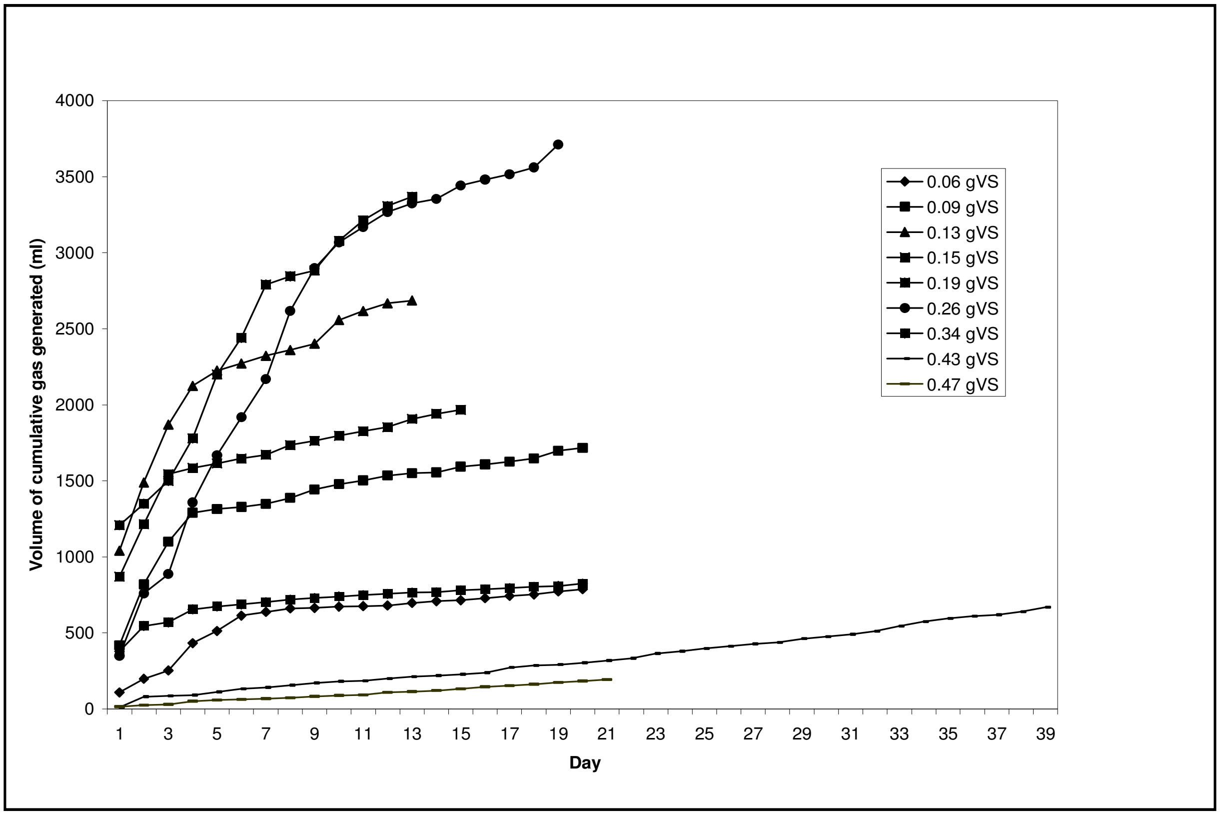
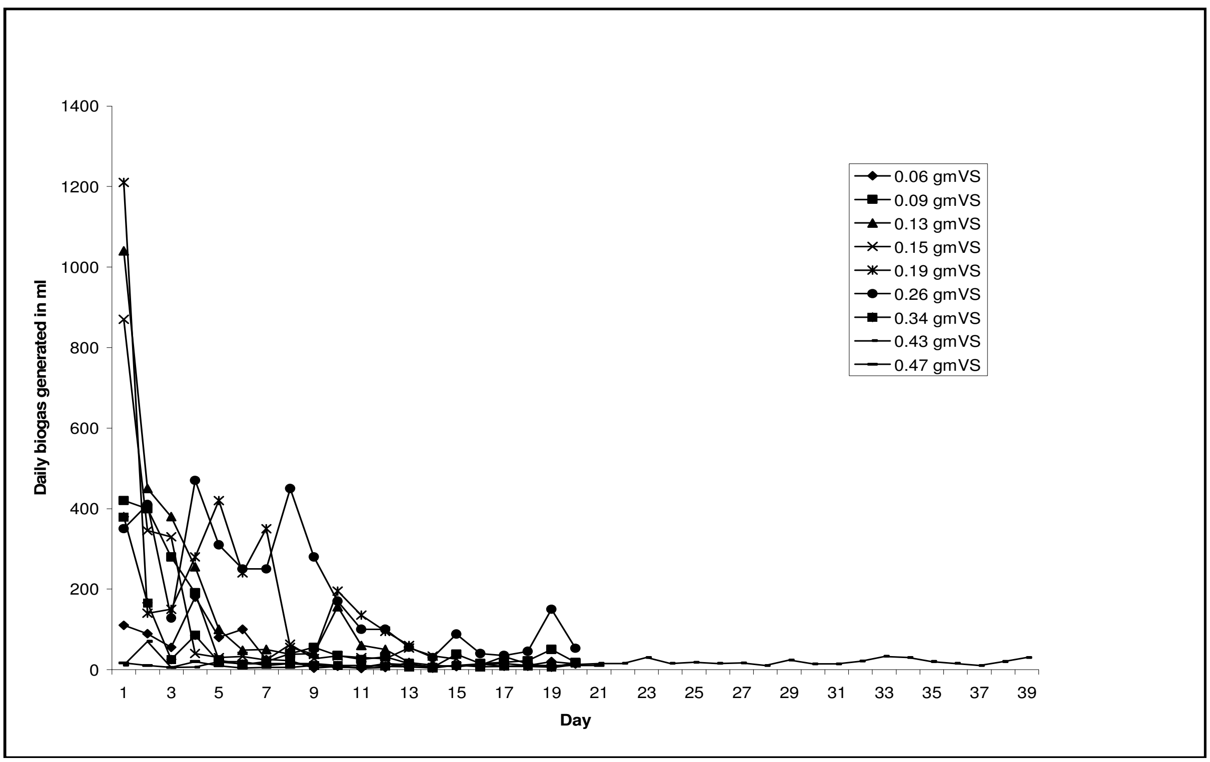
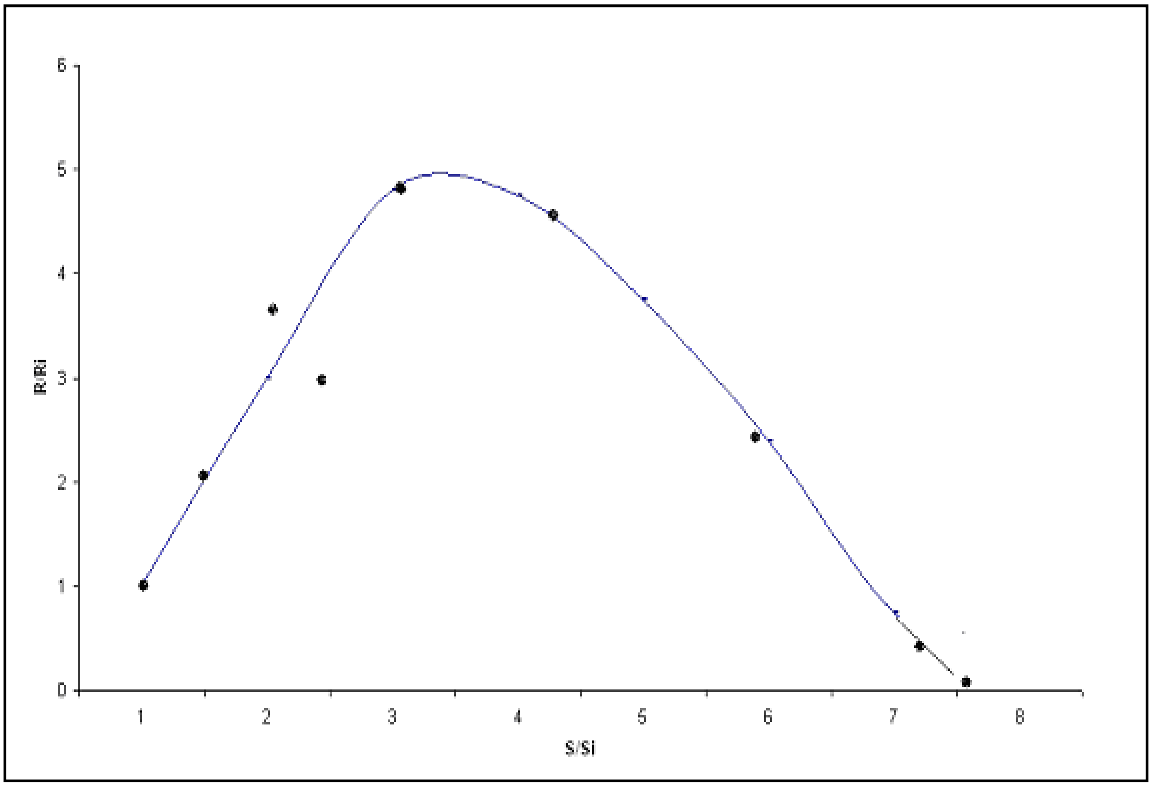



**Figure -1**
**Variation of cumulative biogas production versus days for different substrate loading**




**Figure–2**
**Variation of daily biogas production versus days for different substrate loading**




**Figure–3**
**Variation of mean production of methane (R/Ri) as a function of relative substrate concentration (S/Si)**

**Table-5**
**Equations for polynomial and linear models**

| Substrate loading gmVS | Polynomial equation | $R^2$ Value | Linear Equation | $R^2$ Value |
|---|---|---|---|---|
| 0.06 | $y = -2.8107x^2 + 87.743x + 83.632$ | 0.923 | $y = 28.719x + 300.05$ | 0.7367 |
| 0.09 | $y = -3.891x^2 + 127.04x + 622.54$ | 0.8688 | $y = 45.333x + 922.15$ | 0.7274 |
| 0.13 | $y = -12.879x^2 + 292.82x + 964.21$ | 0.9395 | $y = 112.52x + 1415$ | 0.8212 |
| 0.15 | $y = -5.6661x^2 + 147.57x + 950.29$ | 0.8833 | $y = 56.914x + 1207.2$ | 0.7708 |
| 0.19 | $y = -10.742x^2 + 344.09x + 726.92$ | 0.984 | $y = 193.71x + 1102.9$ | 0.9518 |
| 0.26 | $y = -11.582x^2 + 416.05x - 92.525$ | 0.9901 | $y = 172.83x + 799.3$ | 0.8852 |
| 0.34 | $y = -1.3438x^2 + 44.041x + 442.95$ | 0.8962 | $y = 15.822x + 546.42$ | 0.7528 |
| 0.43 | $y = 0.1384x^2 + 10.289x + 51.552$ | 0.9958 | $y = 15.825x + 13.725$ | 0.9881 |
| 0.47 | $y = 0.0752x^2 + 6.9033x + 14.687$ | 0.9945 | $y = 8.5056x - 4.9424$ | 0.9872 |

**Kinetic Study:** Kinetic studies of anaerobic digestion process are useful to predict the performance of digesters. Kinetic studies are also helpful in understanding inhibitory mechanisms of biodegradation. First order kinetic models are the simplest models applied to the anaerobic digestion of complex substrates as they provide a simple basis for comparing stable process performance under practical conditions. Therefore a first order model based on the availability of substrate as the limiting factor was used [23-27] to evaluate the performance in the present study.

The basic equation is $dB / dt = -kB$

where 'k' is the first order substrate utilization rate constant ($time^{-1}$) and B (mg/l) represents the biodegradable substrate concentration. On integration the equation becomes

$B / B_0 = \exp(-kt)$

where $B_0$ (mg / l) represents initial substrate concentration. Substrate concentration can be correlated with biogas production (G), as mentioned $(G_\infty - G) / G_\infty = B / B_0$

Where $G_\infty$ is the maximum biogas production at infinite digestion time

From the above two equations, the integrated equation for the first order model which gives analytical relation between the volume of biogas produced and digestion time was obtained and used to quantify the extent of process inhibition [28] as follows.
$$G = G_\infty [1 – \exp (-kt)]$$

Where k ($time^{-1}$) is the first-order biogas production rate constant.
Taking Napierian logarithms in the above equation and ordering the terms the following equation is obtained.
$$\ln[G_\infty / (G_\infty - G) ] = kt$$

Indicating that $\ln[G_\infty / (G_\infty - G) ]$ versus t should give a straight line of slope equal to k with intercept zero. The value of $G_\infty$ has been considered equal to the volume of biogas accumulated at the end of each experiment. Representation of the experimental data in the above equation gives straight lines with intercept practically zero and slope equal to k. The values $G_\infty$ of k obtained from a non-linear regression analysis using Curve Expert[29, 30]. The values of kinetic constant markedly decreased from 0.22 to 0.058 when the substrate concentration increased from 0.26gmVS to 0.47gmVS showing the occurrence of inhibition beyond 0.26 gmVS.

## Conclusion

From the results obtained, it can be concluded that, the vegetable wastes containing high carbohydrates are amenable to anaerobic digestion process and the maximum gas production was observed during 5-10 days of digestion. This shows that carbohydrates have been broken down much faster than the proteins and fats present in the waste and produced the gas. The mean methane production rate calculated on the basis of substrate concentration and the corresponding mean gas production show that the reactors can be operated safely till 0.26gmVS loading beyond which inhibition of the process started. Similar trend was observed, in the specific rate constant value, k, calculated for the first order kinetics. The application of factorial (empirical) analysis using predictive models shows polynomial function seemed to be more reliable in predicting gas production in anaerobic digestion of vegetable wastes. Based on these observations further studies are in progress in continuous reactors for various loading ranges.

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