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Regression Modeling and Analysis of Factor-Interactive Effect on Anaerobic Biodegradation Process for Biogas Generation

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Abstract - In this study, regression modeling and analysis of factor-interactive effect on anaerobic biodegradation process (ABP) of food residues mixed with fruit-waste is presented. An experimental anaerobic digester simulating mesophilic conditions of most urban solid waste dumpsites was developed. The goal was to carry out regression modeling on anaerobic biodegradation process for biogas generation. The main- and interactive-effects of initial-pH, ash-loading and leachate-level were investigated. Response surface methodology with miscellaneous 3-level factorial design was employed. A second-order polynomial regression equation was generated that predicted biogas generation rate (BGR). Results indicated that within the experimental range of factors applied there was a single factor significant effect of initial-pH and ash-loading on ABP while leachate-level single effect was observed to be insignificant ($\alpha < 0.05$). The two factor interactive-effects of initial-pH/ash-loading and leachate-level/ash-loading were found to be significant while that of initial-pH/leachate-level interactions was not significant. Verification tests yielded maximum BGR values that were in good agreement with predicted values thereby validating the regression model.

Keywords - Regression Modeling, Factor-Interactive Effect, Anaerobic Biodegradation, Biogas Generation, Response Surface Methodology, Tanzania

1. Introduction

It has been observed that urban solid waste (USW) exists abundantly in most developed and developing cities of the world. This abundance brings with it great challenges and opportunities to most USW management processes. One of the important functions in USW management strategies is energy recovery specifically in form of biogas through anaerobic biodegradation process (ABP). This plays a vital role by providing a useful product and at the same time mitigating problems of USW management and disposal. In rural Tanzania there is a high potential for biogas generation using animal refuse as the main feedstock to the biodigesters. The opportunities for biogas generation include large numbers of zero-grazed animals, high cost of firewood and its shortage, especially in Rungwe district of South-west Tanzania (Mwakaje, 2008). However, the establishment of rural biogas plants has been offset by factors such as affordability, water shortage, inadequate expertise and poorly constructed biogas plants leading to ineffective performance. On the other hand, in urban Tanzania different opportunities exist for biogas production and use among which is the abundance of organic solid waste (OSW) which is highly biodegradable and can be used as suitable digester feedstock (Kivaisi & Mukisa, 2000). Existing literature show substantial amount of OSW generated in Tanzania with the biggest fraction being biodegradable and useful for ABP. A study on the physical characteristics of solid waste (SW) revealed that the SW collected from various dumpsites in Kinondoni Municipality, Dar es Salaam City, contained about 50% of the plant biomass which was capable of bioconversion (Mtui & Nakamura, 2005; Oberlin, 2013). This showed that more than half of the SW collected in Dar es Salaam City contained biodegradable matter. Existing data also showed that the initial-pH, leachate-level and ash-loading additives affect the ABP but the extent of the effect was not sufficiently documented. A combination of the factors and how they interactively affect the ABP was not documented. This motivated the current research to model the ABP and establish the main- and interactive-effects of factors on the ABP.

2. Literature Review

Literature shows that the anaerobic biodegradation of organic solid waste (OSW) is often complex because it involves many different factors and reaction pathways. These factors include a good variety of micro-organisms, environmental factors such as temperature, moisture content, presence of inorganic salts and oxygen which determine specific reaction pathways, structure and composition of substrate organic matter, volatile fatty acids and pH, presence of nutrients such as phosphates, nitrates, and ammonium compounds, ions, carbon and nitrogen nutrient levels, salinity and the overall composition and structure of the SW matrix (Banks & Lo, 2003; Lay *et al*., 2005; Jingura & Matengaifa, 2009; Amani *et al*., 2010; Wanasolo *et al*., 2013; Okonkwo *et al*., 2013). This implies that there is no single factor that could be claimed to have sole responsibility for the success of the biodegradation process. As a result, the biodegradation process is dependent on the many various factors and components present at play mainly as individual factors and also in factor-interaction. An understanding of the effects of individual and combined factors on the ABP was necessary for achieving maximum and good performance of the ABP (Wang *et al*., 2005; Yossan, 2012; Membere *et al*., 2013; Provenzano *et al*., 2013). It has also been shown that the purpose of regression modeling and experimentation has always been to improve, analyze and predict response (Shi *et al*., 2010; Saraphirom & Reungsang, 2010; Nath & Das, 2011). This implies that there was need for modeling and experimentation to improve processes beyond experimental data and conditions. Consequently, many researches involving regression modeling and optimization (Gummadi *et al*., 2009; Anderson & Whitcomb, 2010), have been done using design of experiment (DOE) methodologies and techniques such as response surface methodology (RSM) and central composite design (CCD) that are equipped with abilities to analyze, improve and predict response. The RSM by Box-Behnken design was applied to determine individual and interactive-effects of food-waste constituents as co-substrates for biogas production from sewage sludge (SSL) (Kim *et al*., 2007). Results showed that the biogas generation rate (BGR) was affected by the amount of vegetable and meat waste as co-substrates on the SSL. Optimum conditions for BGR were determined. This also showed that Box-Behnken design tool can be used to improve the biodegradation of food-waste co-substrates. Also, substrate particle size was optimized using RSM regression modeling among other techniques for anaerobic biodegradation to produce biogas (Izumi *et al*., 2010; Tumutegyereize *et al*., 2011). This showed that with the RSM tool, better BGR values from biodegradation using substrate particle size were achieved. In addition, an augmented design of mixture methodology was employed to design the mixture composition using RSM techniques for the anaerobic co-digestion (Rao & Baral, 2011). Results showed that the RSM design technique was appropriate for modeling of biogas generation. This implied that through use of mixed design methodology the BGR was improved. Furthermore, the anaerobic co-digestion of biodegradation factors were also modeled using RSM technique (Han *et al*., 2012), and optimum conditions were identified and cumulative biogas yield predicted. The mixing ratio and alkalinity showed greatest individual and interactive-effects on cumulative biogas yield. Confirmatory results were reproducible showing that the RSM approach was appropriate methodology for the study. This implied that the RSM technique can be extended beyond solving factor-interaction problems to modeling and prediction of response outside experimental conditions. In general, the RSM tool and design technique has been shown to be a useful and robust tool in modeling and simulation studies such as for biogas generation. It was, therefore, adopted in the present study to design, analyze and model the ABP for biogas generation.

3. Materials and Methods

The experimental setup included a set of anaerobic biodigesters, pumping system, flow conduits, biogas collection and measuring unit, temperature probe, pressure measuring gauge and leachate collection unit. A batch type of digesters in series was operated under mesophilic conditions of temperature range from 28 to 38℃ and over initial-pH range from 3.5 to 11.5. The RSM with miscellaneous 3-level factorial design was employed to analyze the data and model the BGR response. A three-factor combination of thirty two experiments were designed, randomized and performed over a period of three months. Randomization was employed to eliminate bias and avail equal opportunity for each experimental run. Randomization also enhanced the reliability and validity of statistical estimates of output data, especially the regression model. The initial-pH values were always set at particular levels and the recording for BGR values corresponding to particular initial-pH values were taken within 10 to 30 min of experimentation. In the modeling and simulation, the pH was varied at initial conditions as initial-pH according to the determined regression model. The leachate-level and ash-loading were kept constant at their centre-points which were control points in the regression model while the initial-pH value was varied between the low, mid- and high-values. This procedure was repeated for other factors of leachate-level and ash-loading.

4. Results and Discussion

4.1. Determination and Analysis of Regression Model Equation

Data analyses yielded regression model Equations (1) and (2) in actual and coded terms, respectively. The regression equations

were significant with the initial-pH (*a*) and ash-loading (*c*) having significant individual effects on the regression model while leachate-level (*b*) was not significant ($\alpha < 0.05$). The two factor interactive-effects were significant for the initial-pH/ash-loading and leachate-level/ash-loading interactions, while that due to initial-pH/leachate-level interaction was not significant. This implied that a combination of initial-pH/leachate-level terms did not significantly contribute to the regression model and, therefore, had no significant effect on the BGR response.

$$\text{BGR (ml/min)} = 0.95 - 0.39a - 0.08b + 0.30c - 0.02ab - 0.25ac - 0.39bc \quad (1)$$

$$\text{BGR (ml/min)} = 0.30 - 0.05a + 1.13b + 6.70c - 3.22ab - 4.16ac - 3.74bc \quad (2)$$

The regression Equation (1) shows that the initial-pH, (*a*), and ash-loading, (*c*), have higher contributions to BGR response than leachate-level, (*b*), since the coefficients - 0.39 and + 0.30, respectively, are numerically higher than that for leachate-level, - 0.08. Also, the effect of initial-pH in the regression model decreases with increase in initial-pH while that of ash-loading increases with increase in ash-loading. The factor that has least impact in the regression model is leachate-level since it has the lowest numerical coefficient. The interaction coefficients of the regression model in actual terms shows that the initial-pH/ash-loading interaction has the highest contribution in the regression model. This is because of the high values of numerical coefficient in the regression model. The data generated by regression model Equation (2) is graphically compared to the experimental data using regression analysis shown in Figure 1. The data shows that the percent residuals are generally low with few exceptions above 50% of the actual values. This implies that the error discrepancies between experimental data and regression model data are low and within acceptable limits. The regression line of best fit shows a negative slope indicating that the percent residuals become low at high BGR values. This also implies that the predicted BGR responses at high biogas rates are closer to the experimental values than the predictions at low BGR values.

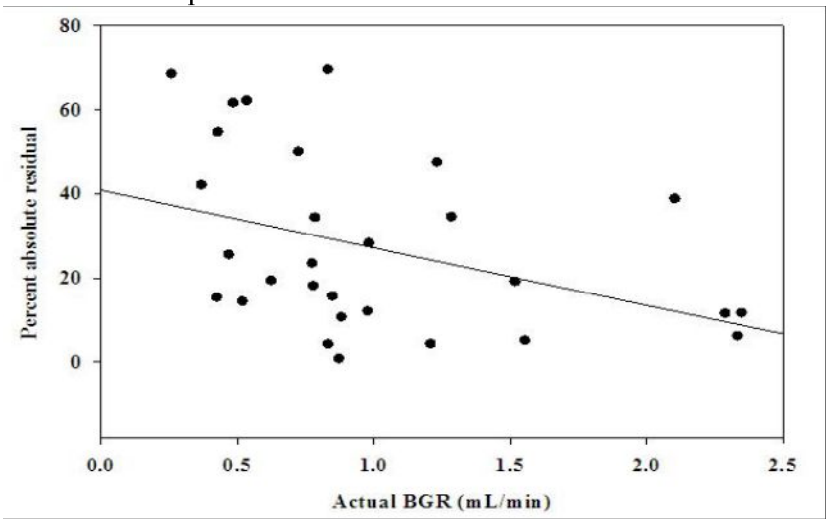


Fig. 1. Comparison of model and experimental biogas generation rates in terms of percent absolute residuals

4.1.1. Error Analysis of Regression Model Coefficients

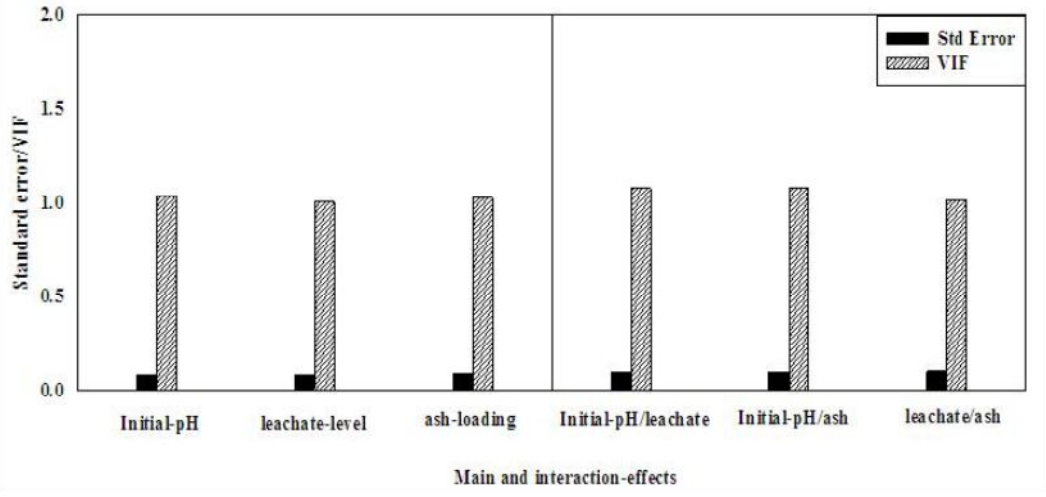


Fig. 2. Comparison of standard error and variance inflation factor for main and interactive-effects

The regression model coefficients and error estimation were determined at 95% confidence level. The data is illustrated graphically for comparison of extent of the standard error (SE) and the variance inflation factor (VIF) as shown in Figure 2. The graphical data shows that the SE is very low (≤ 0.1) for both the main and interactive-effects. This implies that there is high accuracy for the regression model coefficients of Equation (1) and (2). Therefore, the regression model obtained is appropriate representation of the valid relationship between biodegradation factors and the BGR response. The VIF is also low, approximately unity, which also implies that the modeled biodegradation factors are highly independent making the model robust.

4.1.2. Model Validation

The regression model of Equation (1) and (2) was validated using standard error (SE) analysis plots. These plots are a useful check for any inconsistency between the fitted regression model and the experimental data set of the response variable that can adversely affect the regression model performance. The 3D SE plots are also a surface representation of mean SE distribution of response data set for initial-pH/leachate-level interactions at ash-loading of 300 g ash/kg VS centre-point, initial-pH/ash-loading interactive-effect at leachate-level of 750 ml centre-point and leachate-level/ash-loading interactive-effect at initial-pH of 7 centre-point, as shown in Figure 3. The data shows two plots: the contour plot at the base and the mean SE surface plot above the base. Contours on the horizontal graph represent the mean SE associated with the response data. Data from the plots show surfaces of evenly distributed and constant error variance of the mean SE of the predicted response data set with the lowest mean SE of 0.06 at the centre-point and the highest at the corners of the cube. This shows the uniformity of error variance distribution around the experimental data set. It implies that the errors are normally distributed and are greatly minimized, which is an indication that the regression model is valid and fits the experimental data. Moreover, the lack-of-fit test is used also to assess whether the regression model fits the data well. The lack-of-fit value obtained is non-significant and this also shows that the polynomial regression model fits well to the experimental data and there are no significant outliers and influential points in the response data space. Therefore, the regression model Equation (1) and (2) represents valid relationship between the BGR response and modeled factors.

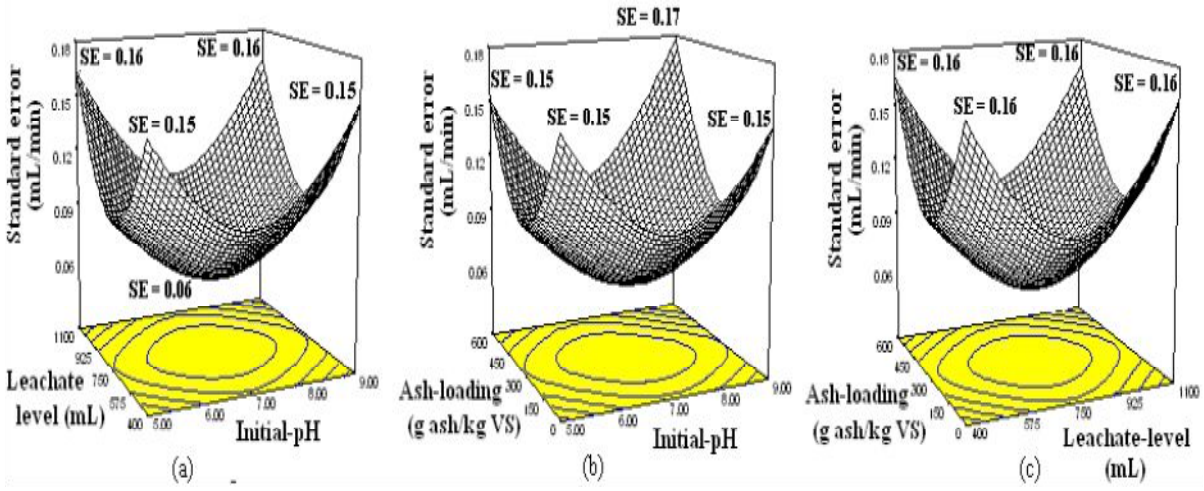


Fig. 3. Mean standard error distribution for regression model validation at centre-points

4.2. Analysis of Two-factor Interactive-effects on Biogas Generation Rate using Contour Plots

The BGR response due to two-factor interactive-effects of independent variables is illustrated on 2D plots. The 2D data presentation is important for model display and establishment of response patterns at different independent coordinate variables and also for visibly determining the best independent maximum coordinate variables responsible for effective and efficient biodegradation process. The contour plots obtained are shown in Figure 4. The response change due to factor interactions is shown by the color shades starting from the lowest response indicated by the deep blue color to the highest shown by the yellow color-shade. The interactive-effects are analyzed at centre-points because there are no possible significant effects contributed by factors whereas extreme points are ideal for causing significant effects on the response.

The data shows that the interactive-effect of initial-pH/leachate-level on BGR increases with decrease in initial-pH; with the highest value observed at contour line of 1.35 ml/min and almost remains constant with increase in leachate-level as seen in part (a) of Figure 4. The interactive-effect of initial-pH/leachate-level is such that an increase in BGR is achieved with a small decrease in initial-pH and a very large decrease in leachate-level as seen by a shift from contour line 1.10 to 1.24 ml/min. Therefore, there is no significant interactive-effect of initial-pH/leachate-level on BGR within the limits of experimental factors studied. Along the two diagonals, increasing initial-pH and leachate-level simultaneously results in BGR decrease and increasing

initial-pH simultaneously with decrease in leachate-level also result in BGR decrease. The converse is true, i.e., simultaneous decrease in initial-pH with either decrease or increase in leachate-level results in BGR increase. This also shows that there is no interactive-effect of initial-pH/leachate-level on BGR. Again, at constant leachate-level a decrease in initial-pH results in BGR increase; while at constant initial-pH an increase in leachate-level results in almost constant BGR response. This shows that despite the presence and quantity of leachate-level, the BGR can be increased with decrease in initial-pH. Therefore, there is no significant interactive-effect of initial-pH/leachate-level on BGR response. The observed BGR increase could be solely attributed to initial-pH decrease and the linear appearance of the contour lines also implies lack of strong initial-pH/leachate-level interactive-effect on the BGR response.

The interactive-effect of initial-pH/ash-loading is such that the BGR increases with a combined decrease in initial-pH and increase in ash-loading throughout the plotted area. This effect is seen by a movement from a contour plot of 0.69 to 0.81 ml/min in part (b) of Figure 4. The increase with decreasing initial-pH is sharper than the decrease with increasing leachate-level. Also, along the major diagonal, increasing initial-pH and ash-loading simultaneously results in a slight BGR increase to a maximum point followed by a slight BGR decrease, implying that there are maxima along the major diagonal. Along the minor diagonal increasing initial-pH simultaneously with decrease in ash-loading results in BGR decrease. The converse is true, i.e., simultaneous decrease in initial-pH with increase in ash-loading results in BGR increase and there is no maximum point along the minor diagonal. This shows that there is a significant interactive-effect of initial-pH/ash-loading on BGR response. The significant interactive-effect is more at low initial-pH and high ash-loading. This is attributed to the porosity nature of ash particles that is believed to have increased the microbial activity by offering increased surface area of the substrate organic matter thereby causing significant increase in BGR response (Park *et al*., 2005; Augusto *et al*., 2008)

At constant ash-loading increasing initial-pH results in BGR decrease, while at constant low initial-pH values, increase in ash-loading results in BGR increase until the yellow region. At high initial-pH values, increase in ash-loading results in almost constant BGR values. This shows that there is less initial-pH/ash-loading interactive-effect on BGR response at high initial-pH values compared to the interactive-effect at low initial-pH values, attributed to the microbial inactivity at high initial-pH levels.

The interactive-effect of leachate-level/ash-loading at ash-loading of about 200 g ash/kg VS and lower is such that a simultaneous increase in leachate-level and ash-loading results in BGR increase. This is seen by a movement from contour line marked 0.69 to 0.81 ml/min shown in part (c) of Figure 4. While, at ash-loading of 250 g ash/kg VS and above, an increase in BGR is observed with a simultaneous decrease in leachate-level and an increase in ash-loading, as seen by a movement from contour line 1.09 to 1.28 ml/min. This is attributed to the catalytic nature ash particles that increase surface area leading in high BGR response at high ash-loading values. Also, at points near the major diagonal, increasing leachate-level and ash-loading simultaneously results in BGR increase until a maximum point followed by a slight BGR decrease, implying that there are maxima at BGR values near the major diagonal. Near the minor diagonal, an increase in leachate-level simultaneously with a decrease in ash-loading results in BGR decrease until a minimum point followed by increase in BGR response. This also implies that there are minima at points near the minor diagonal. The presence of maxima at points near the major diagonal and minima at points near the minor diagonal implies that there is a saddle point for the BGR value that is both a minimum and maximum. The saddle point is clearly observed as shown by symbol *S* in part (a) of Figure 5 and its saddle surface is shown in part (b).

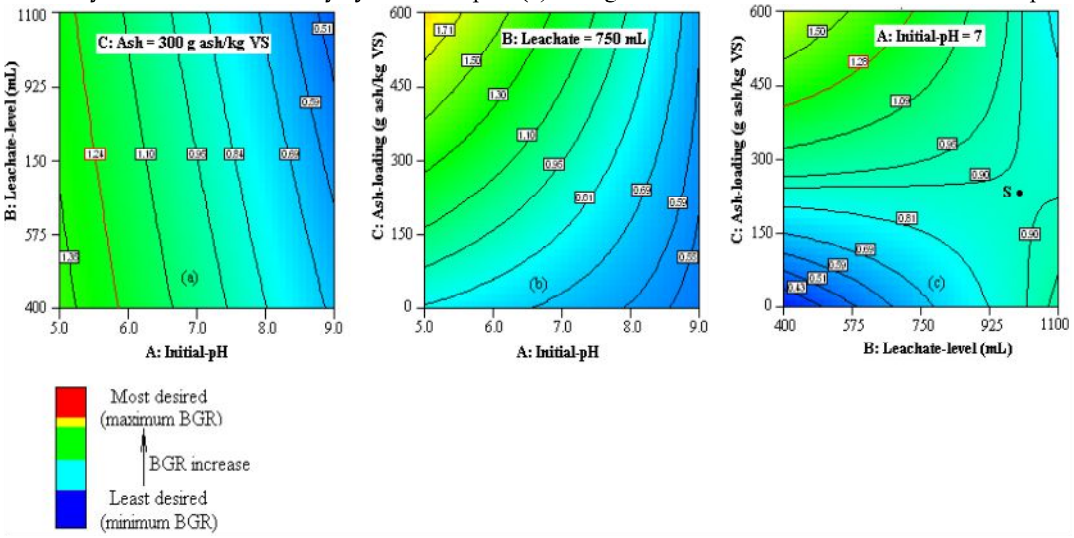


Fig. 4. Two-factor interactive-effect on biogas generation rate

The data in Figure 5 shows that at constant ash-loading of 150 g ash/kg VS and lower, increasing leachate-level results in BGR increase, while at constant ash-loading between 200 and 250 g ash/kg VS increasing leachate-level results in constant BGR

response. At constant ash-loading above 250 g ash/kg VS increasing leachate-level results in BGR decrease. This implies that there is a turning point in BGR at constant ash-loading between 200 and 250 g ash/kg VS at which by increasing leachate-level the BGR trend changes from increasing to decreasing. At constant low leachate-level, increasing ash-loading results in BGR increase; while at constant high leachate-level increasing ash-loading results in BGR decrease. This also implies that there is a turning point at some value of constant leachate-level at which during increase in ash-loading the trend of BGR changes from increasing to decreasing. This phenomenon also implies that there is a saddle point existing within the leachate-level/ash-loading interactive-effect. The saddle point is observed at a contour line with BGR of nearly 0.89 ml/min at leachate-level of around 1015 ml and ash-loading of 240 g ash/kg VS. The parallel lines of 0.89 ml/min contours intersect at 90° and this implies that at constant leachate-level of 1015 ml there is constant BGR of 0.89 mL/min despite the level of ash-loading. The converse is true, i.e., despite the amount of leachate-level at constant ash-loading of 240 g ash/kg VS there is a constant BGR response of 0.89 ml/min. Therefore, for practical purposes the saddle point becomes a critical point that must be avoided since variations in either factor has no impact on the observed BGR values.

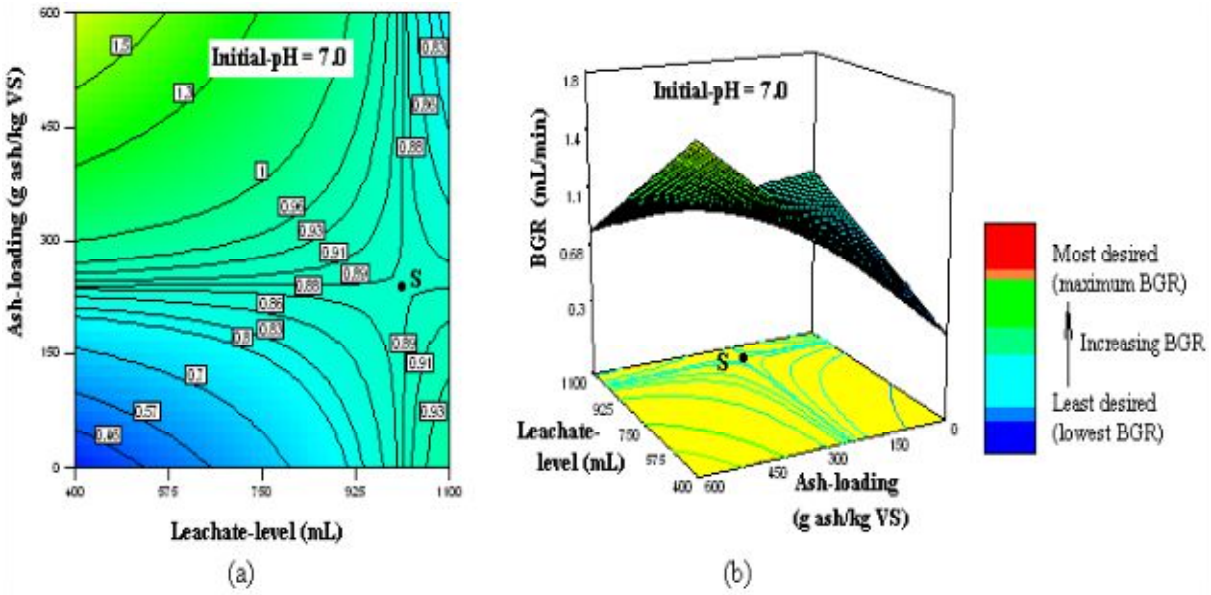


Fig. 5. Saddle point and surface during interactive-effect of leachate-level/ash-loading at initial-pH = 7

4.3. Analysis of Two-Factor Interactive-effect on Biogas Generation Rate Using Surface Plots

The two-factor-interactive-effect is also illustrated using 3D response surface plots as shown in Figure 6. The data shows that there are two highest and close values for the BGR response at leachate-level of 400 and 1100 ml and initial-pH of 5.0, as seen in part (a) of Figure 6. This implies that the interactive-effect of initial-pH/leachate-level on BGR is not significant. At constant leachate-level decreasing initial-pH results in sharp BGR increase. This shows that despite the quantity of leachate-level available the decrease in initial-pH results in BGR increase, attributed to the more active nature of microbial population at moderate initial-pH levels. Also, at constant initial-pH, increase in leachate-level results in small and almost constant BGR changes as seen by the gentle slopes for constant initial-pH. This implies that change in leachate-level at constant initial-pH does not produce significant changes in BGR response. Again, along the diagonals of the surface plot, decrease in initial-pH simultaneously with either decrease or increase in leachate-level results in BGR increase. This also shows that there is no significant interactive-effect of initial-pH/leachate-level on BGR and the sharp BGR increase is attributed to initial-pH decrease but not due to interaction.

However, there is only one peak value of BGR response for the initial-pH/ash-loading interactive-effect on BGR as seen in part (b) with the next highest BGR response far below it. This shows that there is a significant interactive-effect on the BGR occurring at the point of highest BGR response, which is low initial-pH and high ash-loading. At constant low ash-loading increasing initial-pH results in almost constant BGR while at constant high ash-loading increasing initial-pH results in BGR decrease. This shows that there is significant initial-pH/ash-loading interactive-effect at high ash-loading compared to that at low ash-loading. Besides, at constant low initial-pH increasing ash-loading results in sharp BGR increase while at constant high initial-pH increasing ash-loading results in gentle BGR increase. This also shows that the initial-pH/ash-loading interactive-effect is more at low initial-pH than at high initial-pH, resulting in the highest initial-pH/ash-loading interactive-effect observed at low initial-pH and high ash-loading. Furthermore, along the main diagonal simultaneous increase

in initial-pH together with ash-loading results in almost constant BGR shown by the constant yellow/blue color. However, along the minor diagonal simultaneous increase in initial-pH and decrease in ash-loading results in sharp decrease in BGR. This shows that the highest interactive-effect is located along the minor diagonal.

In addition, the interactive-effect of leachate-level/ash-loading on BGR is significant since there is only one peak value of BGR response with the next highest being far below it, as shown in part (c). The data also shows that at constant low ash-loading increasing leachate-level results in BGR increase while at constant high ash-loading increasing leachate-level results in BGR decrease. The BGR increase at low ash-loading and decrease at high ash-loading almost ended at the same BGR value. This shows that there is a counter-check balance in the BGR value that is responsible for an equal BGR increase and decrease. This point is best illustrated in Figure (5b) and it is called a saddle point. Moreover, at constant low leachate-level increasing ash-loading results in sharp BGR increase while at constant high leachate-level increasing ash-loading results in a gentle BGR decrease. This also shows that the leachate-level/ash-loading interactive-effect is more at low leachate-level than at high leachate-level. The increase in BGR at low leachate-level and decrease in BGR at high leachate-level is also attributed to the presence of a saddle point in the neighborhood.

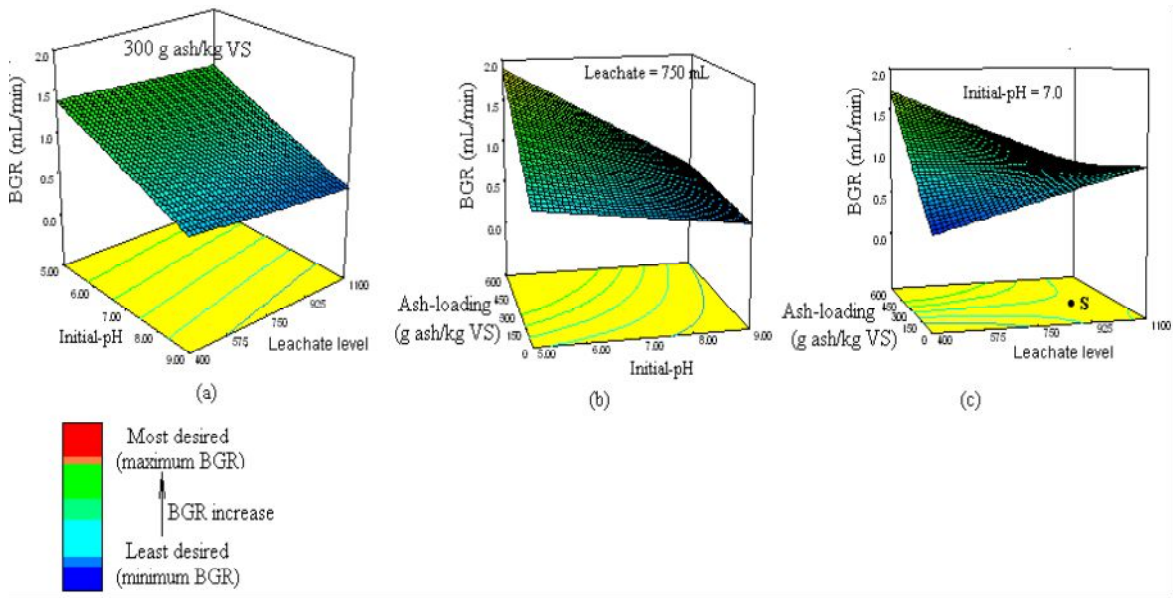


Fig. 6. Surface plots for two-factor interactive-effects on biogas generation rate

5. Conclusion

In conclusion, by analysing and comparing the initial-pH/leachate-level, initial-pH/ash-loading and leachate-level/ash-loading interactive-effects, the initial-pH/ash-loading interactive-effect is prefered since a greater effect on BGR response is observed. There is more factor interactive-effect on BGR with initial-pH/ash-loading than with any other factor interaction such as leachate-level/ash-loading.

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