

Modeling and analysis of biogas generation rate sensitivity to initial-pH, leachate-level and ash-loading during anaerobic biodegradation of organic solid waste

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Abstract: Anaerobic biodegradation of solid waste food-residues mixed with fruit-waste was carried out at mesophilic conditions. The goal was to model the sensitivity of biogas generation rate to initial-pH, leachate-level and ash-loading. Two process parameters were analyzed at centre-points while the third factor was set at low-, mid- and high-levels. The simulation results showed that at initial-pH of 5 (low-level), the biogas generation rate was more sensitive to ash-loading than at high-level of initial-pH values. The minimum and maximum attainable biogas generation rates due to perturbations in ash-loading were 0.79 and 1.89 mL/min, respectively, representing a difference of 1.10 mL/min. A comparison using sensitivity quotient revealed that decreasing leachate-level had a stronger effect on biogas generation rate than increasing it. It was also found that the biodegradation process was over four-times more sensitive to variations in initial-pH than in ash-loading while it was over seven-times more sensitive to variations in initial-pH than in leachate-level. It was concluded that the sensitivity of biogas generation rate was highest to variations in initial-pH and least to variations in leachate-level.

Keywords: Modeling Biogas Generation, Anaerobic Biodegradation, Sensitivity, Mesophilic, Organic Solid Waste Decomposition

1. Introduction

Modeling biogas generation rate sensitivity was an analytical technique used to establish the magnitude of biogas generation rate as a response to different organic solid waste biodegradation factors of initial-pH, leachate-level and ash-loading. The study investigated the extent to which these factors affect individually and interactively the anaerobic biodegradation process (ABP) of fermenting solid waste food-residues mixed with fruit-waste.

The impact of initial-pH on ABP of organic waste has been extensively studied and it was shown to be an important factor affecting the ABP. At mesophilic and thermophilic conditions [1-4], the effect of initial-pH was investigated and the ABP was shown to be favored by slightly acidic initial-pH range at thermophilic temperatures while the optimum product rate was at initial-pH of 6.8 and 5.5. This showed that optimum biogas production was

favored at initial-pH of around 7. Also, one of the important parameters affecting ABP is the moisture content, controlled via leachate re-circulation. The idea of enhancing waste fermentation by re-circulating leachate was first proposed many years ago [5-7]. This suggested that leachate recirculation in biodegradation processes has been in used for some time and may not be a new idea. Leachate re-circulation is stimulatory because it allows a uniform distribution of microbial inoculum, minimizes local nutrient shortages and dilutes potential toxins against microbes [8,9]. This was one way of ensuring an even distribution of inorganic nutrients and micro-organisms in the bio-digester. In the absence of active acetogenic and methanogenic microbial populations, re-circulated leachate caused accumulation of volatile fatty acids (VFA) resulting in rapid initial-pH decrease, inhibiting subsequent biogas production [10-13]. This implied that leachate recirculation required additional care and pre-treatment such as initial-pH adjustments or buffering action to minimize accumulation of

VFA. As a result, a combination of leachate recirculation with proper initial-pH adjustments minimized inhibitory effects of acid accumulation and accelerated waste biodegradation [5, 14]. This technique of initial-pH control against inhibitory effects was employed in the present study.

The properties of ash are important for its utilization in physical-chemical and biochemical processes such as the anaerobic biodegradation of organic waste. Ash has high initial-pH value ranging from 11.0 to 14.0 with average particle size of 230 μm and shows acid neutralization properties [15-17]. This suggested that the high initial-pH of ash could be of importance to the stabilization of VFA accumulation that results in rapid initial-pH decrease. Also, the highly porous carbon and other inorganic particles present in the ash react with water to form circular clusters believed to be responsible for the frothing phenomenon that is observed when ash is mixed with water [18, 19]. This frothing increases the surface area of the reactive material of the reaction medium [19-21]. In the present work, the frothing phenomenon of ash-loading was believed to have made ash-loading additive capable of rendering catalytic properties to the ABP. Consequently, ash-loading positively affected the anaerobic biochemical process as a source of inorganic nutrients and also offered increased surface area responsible for faster biochemical reactions. These properties resulted in modification of ABP by way of altering reaction pathways. This denoted that the carbon content present in ash-additive determined the reaction properties of media where ash-additive is present. Hence, ash-loading was believed to possess catalytic properties during the ABP of the present study. In general, the behaviour of ash-loading additive during the biodegradation process was comparable to its effect when added to acidic soils for fertility improvements in which the highly porous carbon content in ash offer increased surface area, adsorb odours and possess catalytic properties similar to that of activated carbon [22-23]. In view of the above, the sensitivity of biogas generation rate to ash-loading was investigated.

2. Method

A batch type of bioreactors in series was operated under mesophilic conditions of temperature range from 28 to 38°C and over initial-pH range from 3.5 to 11.5. Each set of bioreactor cells was reacted with equal amounts of solid waste food-residues mixed with fruit-waste at varying initial-pH, leachate-level and ash-loading values. Measurements were recorded for the cumulative volume of biogas (CVB) generated in mL and biogas generation rate (BGR) in mL/min within 10 - 30 min of the biodegradation process. During modeling and simulation experiments the leachate-level and ash-loading were kept constant at their centre-points which acted as control points in the regression model while the initial-pH value was varied between the low- mid- and high-levels of 5.0, 7.0 and 9.0, respectively. Back on the experimental rig, the initial-pH was set at the

named values while the CVB readings corresponding to the different initial-pH values were taken.

Predictions and analysis of the main and interactive-effects on BGR at particular points of factor-levels in the design space were achieved with the help of perturbation plots. The perturbation plots also enabled prediction of level of dependence and sensitivity of BGR to the factors. The factor with a steep slope in the perturbation plot indicated that the BGR response was more sensitive to a change in that factor. A gentle slope revealed that the response BGR was less sensitive to a change in that particular factor while a horizontal plot confirmed that there was no BGR response and sensitivity to a change in the factor. The perturbation plots, therefore, helped to identify factors that most affected the BGR response at the experimental conditions. A more accurate analysis using a sensitivity quotient (SQ) was also employed to compare the sensitivity of the ABP to changes in the three independent factors.

3. Results and Discussion

3.1. Biogas Generation Rate Sensitivities to Main-Effects

The BGR sensitivity to variations of main-effects was as shown in Fig. 1. The data denoted that the BGR response was sensitive to changes in both initial-pH and ash-loading as individual factors but it was not sensitive to changes in leachate-level. This was indicated by the steep slopes of both initial-pH and ash-loading lines *aa* and *cc*, respectively, and the gentle slope *bb* of leachate-level. The data also showed that for initial-pH the steep negative slope meant that there was a decrease in BGR with increase in initial-pH while for ash-loading the positive steep slope meant an increase in BGR with increase in ash-loading.

The sensitivity simulations suggested that for all factors kept constant at centre-points, when the initial-pH was varied from 7 to 5, the sensitivity quotient (SQ) was determined to be 1.422 units and when the initial-pH was varied from 7 to 9 the SQ was also 1.422 units. This indicated that the BGR had a constant sensitivity to variations in initial-pH over the entire range of values studied. It also suggested that decreasing or increasing initial-pH had the same impact on the BGR sensitivity, other factors such as microbial population being kept at sufficient levels of activity. When leachate-level was varied from 750 to 400 mL the SQ was determined to be 0.201 units while the SQ was evaluated to be 0.156 units when the leachate-level was varied from 750 to 1100 mL. This demonstrated that decreasing leachate-level had a stronger effect on the BGR than increasing it. It also illustrated that in comparison with variations in initial-pH, the ABP was over seven-times more sensitive to variations in initial-pH than to changes in leachate-level.

Furthermore, when ash-loading was varied from 300 to 0 g ash/kg VS, the SQ was evaluated to be 0.313 units while the SQ was found to be 0.302 units when ash-loading was

varied from 300 to 600 g ash/kg VS. This showed that decreasing ash-loading had a stronger effect to the BGR sensitivity than increasing it. It also indicated that in comparison to initial-pH variations, the ABP was over four-times more sensitive to initial-pH variations than to variations in ash-loading. Overall, the ABP was more sensitive to variations in initial-pH (SQ = 1.422 units), followed by variations in ash-loading (SQ = 0.313 units) and it was least sensitive to variations in leachate-level (SQ = 0.201 units).

In order to visually compare the minimum and maximum attainable BGR values due to main-effects of initial-pH, leachate-level and ash-loading, the data in Fig.1 was presented graphically as shown in Fig. 2. The data signified that initial-pH had the maximum predicted and attainable BGR at its low-level and the minimum at its high-level, with the maximum attainable BGR of almost more than twice the minimum value. This implied that the BGR response to initial-pH at low-level was more than twice that amount at high-level. Therefore, the changes in initial-pH resulted in significant effect ($\alpha < 0.05$) to the BGR response. The leachate-level revealed maximum predicted and attainable BGR at low-level and minimum at high-level with maximum attainable BGR of slightly more than the minimum value. This implied that the change in BGR due to variations in leachate-level was almost of the same magnitude. Therefore, changes in leachate-level did not show significant effect on the BGR response.

The ash-loading showed a maximum attainable BGR at the high-level and minimum at its low-level with the maximum attainable BGR of almost double the minimum. This also revealed that the BGR response to variations in ash-loading at high-level was twice that at low-level.

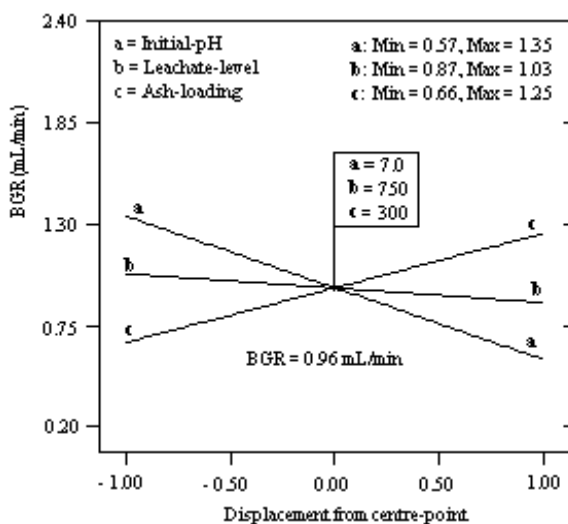


Figure 1. Modeling and analysis of initial-pH, leachate-level and ash-loading sensitivities to biogas generation rate

The data also meant that the BGR response at low factor-levels decreased in order of initial-pH > leachate-level > ash-loading while that at high factor-levels increased in order of initial-pH < leachate-level <

ash-loading. This denoted that for low factor-levels the highest amount of BGR occurred at initial-pH while for high factor-levels the highest quantity of BGR occurred at ash-loading. The data also proved that the maximum attainable BGR response had a minimum value at low leachate-level while the minimum predicted BGR response had a maximum value at high leachate-level. This was an indication that leachate-level at its low-level offered the least maximum attainable BGR response.

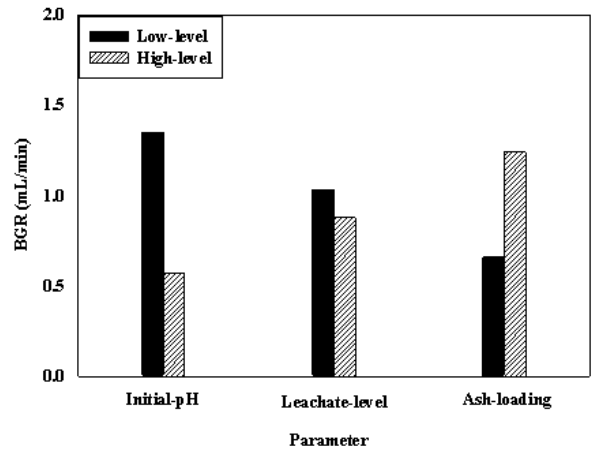


Figure 2. Minimum and maximum attainable biogas generation rates of main-effects

3.2. Biogas Generation Rate Sensitivity to Variations in Leachate-Level and Ash-Loading at Constant Low and High Initial-pH Values

The BGR response to variations in leachate-level and ash-loading was illustrated graphically as shown in Fig. 3. The data showed that the magnitude of BGR response to changes in ash-loading was almost ten-times that to changes in leachate-level at constant initial-pH of 5.0. It was almost four-times that of leachate-level at constant initial-pH of 7.0. However, the magnitude of BGR response to changes in ash-loading was half that observed to changes in leachate-level at constant initial-pH of 9.0. The data also meant that the amount of BGR response to changes in ash-loading decreased sharply with increasing initial-pH while that to changes in leachate-level increased sluggishly with increasing initial-pH. Therefore, in order to attain better results for the magnitude of BGR response, variations in ash-loading were preferred to changes in leachate-level at constant initial-pH of 5.0.

At constant initial-pH of 5, the values of SQ for variations in leachate-level ranged from 0.079 to 0.092 units, while the SQ for variations in ash-loading ranged from 0.400 to 0.415 units. This suggested that at constant initial-pH of 5, the variations in ash-loading had more impact on BGR response than variations in leachate-level. It also showed that the sensitivity of BGR to variations in ash-loading was over four-times more than the variations to leachate-level. Furthermore, at constant initial-pH of 9, the value of SQ for variations in leachate-level was constant at

0.376 units, while the SQ for variations in ash-loading ranged from 0.07 to 0.088 units. This meant that at constant initial-pH of 9, variations in leachate-level had more effect on the BGR response than variations in ash-loading. It also indicated that the sensitivity due to variations in leachate-level was more than four-times that due to variations in ash-loading. Therefore, the level of acidity in the bioreactor cell determined the sensitivity of the ABP to leachate-level and ash-loading.

The BGR response to interactive-effect of leachate-level/ash-loading was determined as shown graphically in Fig. 4. The ash-loading was plotted on the horizontal-axis while the leachate-level was set at the two extreme points of 400 and 1100 mL shown by the red dashed-lines for each of the initial-pH values of 5.0, 7.0 and 9.0. The BGR response and interaction was shown on the vertical-axis. The data showed that there was same magnitude of interactive-effect between leachate-level/ash-loading. This was indicated by the two red dashed-lines not being parallel, ($\Delta BGR_1 < \Delta BGR_2$), for all the initial-pH levels. This proposed that the interactive-effect of leachate-level/ash-loading influenced BGR response more than when each of the factors was present alone. Also, the BGR response was different in the three plots with the highest response obtained at initial-pH of 5 and decreased with increase in initial-pH. Since the interactive-effect was of the same magnitude for all initial-pH values, it signified that the highest BGR response obtained at initial-pH of 5 could be attributed to the high BGR response than to interaction between the factors.

3.3. Biogas Generation Rate Sensitivity to Variations in Initial-pH and Ash-Loading at Constant Low and High Leachate-Levels

The BGR response to variations in initial-pH and ash-loading at constant values of leachate-levels was illustrated graphically in Fig. 5. The data showed that the magnitude of BGR response to variations in ash-loading was twice that to initial-pH at constant leachate-level of 400 mL but lower for ash-loading than for initial-pH at leachate-level of 750 mL and much lower at 1100 mL leachate-level. The data exhibited a drastic decline in BGR response to variations in ash-loading with increasing leachate-level. The BGR response to changes in initial-pH was almost four-times that to variations in ash-loading at constant leachate-level of 1100 mL. The BGR response decreased slightly at leachate-level of 750 and 400 mL. This illustrated the fact that the BGR response to variations in initial-pH decreased slightly with decreasing leachate-level or increased slightly with increasing leachate-level. Therefore, at constant low leachate-level there was low BGR response prediction to initial-pH but high BGR response predictions to ash-loading. In effect, the BGR response to changes in ash-loading decreased sharply with increasing leachate-level while that due to changes in initial-pH increased slightly with leachate-level. Consequently, perturbations at low leachate-level were preferred because

of high BGR response.

Additionally, at constant leachate-level of 400 mL the SQ for variation of BGR response with initial-pH ranged from 1.223 to 1.257 units, while that for BGR variation with ash-loading ranged from 0.66 to 0.67 units. This information showed that variation in initial-pH had more effect to BGR response than variation in ash-loading since $1.257 > 0.67$ units. It also revealed that the sensitivity of BGR response to initial-pH was almost twice that to ash-loading variation. At constant leachate-level of 1100 mL, the SQ for variation of BGR response with initial-pH was constant at 1.63 units, while the SQ for variation with ash-loading ranged from 0.102 to 0.114 units. This was an indication that variation in initial-pH had slightly more effect on the BGR response than variation in ash-loading.

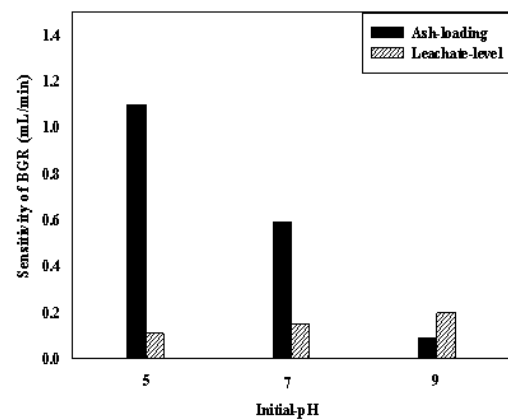


Figure 3. Sensitivity of biogas generation rate to changes in leachate-level and ash-loading at different initial-pH levels

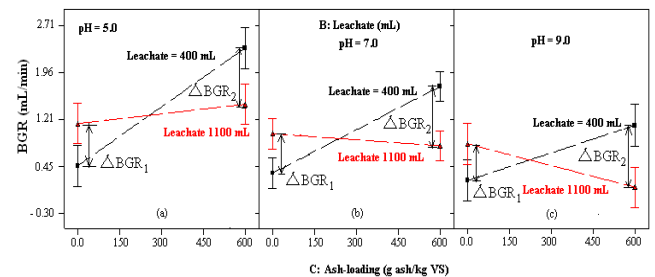


Figure 4. Two-factor interactive-effect and sensitivity of BGR to leachate-level/ash-loading interactions at different initial-pH values

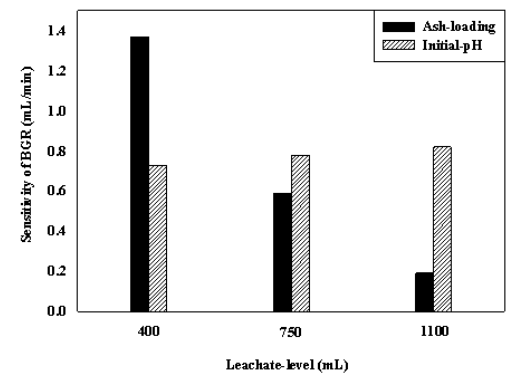


Figure 5. Modeling sensitivity of biogas generation rate to initial-pH and ash-loading at different leachate-levels

The interactive-effect of initial-pH/ash-loading on BGR response was plotted at constant leachate-levels as shown in Fig. 6. The data indicated that the two red dashed-lines were not parallel for all values of constant leachate-level. This implied that there was an interactive-effect of initial-pH/ash-loading on BGR response. The data also demonstrated that the interactive-effect of initial-pH/ash-loading was significant ($\alpha < 0.05$) at 400 mL of constant leachate-level as shown by non-overlap, ($\Delta BGR_1 > \Delta BGR_2$), of the range of plotted areas in the two red dashed-lines as seen in part (a) of Fig. 6. The interaction was also significant at 750 mL of leachate-level but only at initial-pH of 6.0 and lower as shown in part (b) while it was not significant for the 1100 mL of leachate-level as seen in part (c). Also, the BGR response was of the same magnitude in the three plots as shown by equal slopes of the red dashed-lines. Therefore, the highest BGR response obtained at leachate-level of 400 mL could be attributed to the high interactive-effect between the two factors.

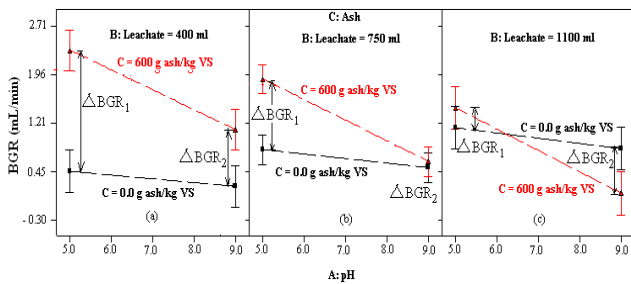


Figure 6. Two-factor interactive-effect and sensitivity of BGR to initial-pH/ash-loading interactions at different leachate-levels

3.4. Biogas Generation Rate Sensitivity to Variations in Initial-pH and Leachate-Level at Constant Low and High Ash-Loading Values

The BGR response to variations in initial-pH and leachate-level at constant ash-loading values was also illustrated graphically as shown in Fig. 7. The data demonstrated that the magnitude of BGR response to changes in leachate-level was more than twice the amount to changes in initial-pH at constant ash-loading of 0.0 g ash/kg VS added, but much lower at constant ash-loading of 300 g ash/kg VS added with the amount of almost less than a quarter of that for initial-pH. The amount of BGR response to changes in initial-pH was higher than that to changes leachate-level at constant ash-loading of 600 g ash/kg VS added. Also, it was observed that the magnitude of BGR response to changes in initial-pH increased gradually with ash-loading while that to changes in leachate-level was lowest at 300 and highest at 600 g ash/kg VS added. Therefore, for better attainable BGR response, the perturbations with initial-pH at constant ash-loading of 600 g ash/kg VS added were preferred.

Furthermore, the magnitude of BGR response to variations in interactive-effect of initial-pH/leachate-level was also plotted at constant ash-loading as shown in Fig.8. The data showed that the two red dashed-lines were nearly

parallel, ($\Delta BGR_1 \approx \Delta BGR_2$), for all values of constant ash-loading. This proved that there was almost no interactive-effect of initial-pH/leachate-level on BGR response. The data also revealed that the very small interactive-effect of initial-pH/leachate-level was not significant ($\alpha < 0.05$) and the non-overlap of the end-bars due to parallel and less closeness of plotted data range as seen in parts (a) and (c) could have been due to experimental error but not due to factor-interaction. Also, the BGR response was different in the three plots with the highest response obtained at constant ash-loading of 600 g ash/kg VS and decreased with decrease in ash-loading. Since the interactive-effect was not observable, it implied that the highest BGR response obtained at constant ash-loading of 600 g ash/kg VS could be attributed to high BGR response than to interaction between the factors.

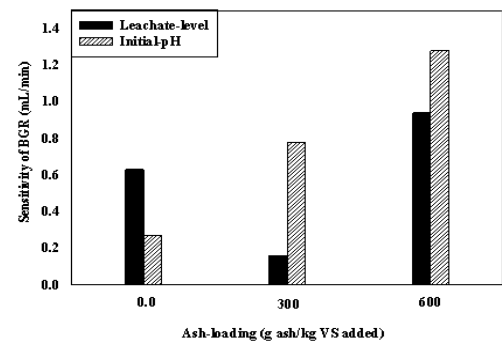


Figure 7. Modeling sensitivity of biogas generation rate to initial-pH and leachate-level at different ash-loading

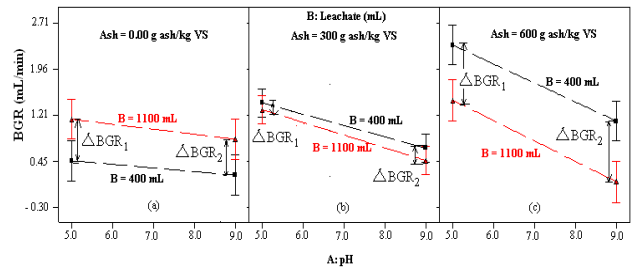


Figure 8. Two-factor interactive-effect and sensitivity of BGR to initial-pH/leachate-level interactions at different ash-loading values

Table 1. Summary of simulation results for sensitivity of biogas generation rate to interactions between initial-pH, leachate-level and ash-loading

Factor combination	Sensitivity	Interaction	Maximum biogas rate due to:
Leachate/ash-loading	Different	Same	Sensitivity
Initial-pH/ash-loading	Same	Different	Interaction
Initial-pH/leachate-level	Different	No interaction	Sensitivity

A summary of simulation results for the magnitude and sensitivity of BGR to interactions between initial-pH, leachate-level and ash-loading was as shown in Table 1. The data confirmed that the maximum BGR response was due to high sensitivity than interactions between leachate-level/ash-loading and initial-pH/leachate-level, while the maximum BGR response was due to

interactive-effect between initial-pH/ash-loading than due to BGR sensitivity.

4. Conclusion

The experimental investigation helped to reveal conditions necessary for achieving best output biogas generation rates from anaerobic biodegradation of solid waste food-residues mixed with fruit-waste. Based on the experimental results, it was concluded that the change in initial-pH had the greatest effect on biogas generation rate response. It was also concluded that the biodegradation process was over 4 times more sensitive to variations in initial-pH than in ash-loading, while it was over 7 times more sensitive to variations in initial-pH than in leachate-level. Also, it was deduced that decreasing leachate-level had a stronger effect on the BGR response than increasing it. It was also inferred that decreasing ash-loading had a stronger effect to the BGR response than increasing it. Overall, the ABP was more sensitive to variations in initial-pH, followed by variations in ash-loading and it was least sensitive to variations in leachate-level. Additionally, the maximum observed BGR response was due to high sensitivity than interactions between leachate level / ash-loading and initial-pH / leachate level, while the maximum BGR response was due to interactive-effect between initial-pH/ash-loading than due to BGR sensitivity

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