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Biogas Recovery from Anaerobic Co-Digestion of Poultry House Wastes for Clean Energy Production

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ABSTRACT

Anaerobic digestion is a technology widely used for treatment of organic waste for biogas production as a source for clean energy. In this study, poultry house wastes (PHW) material was examined as a source for biogas production. The effects of inoculum addition, pretreatment of the substrate, and temperature on the biogas production were taken into full consideration. Results revealed that the effect of inoculum addition was more significant than the alkaline pretreatment of raw waste materials. The biogas recovery from inoculated waste materials exceeds its production from wastes without inoculation by approximately 70% at mesophilic conditions. Whereby, the increase of biogas recovery from pretreated wastes was by 20% higher than its production from untreated wastes at mesophilic conditions. The thermophilic conditions improved the biogas yield by approximately 73%. The kinetic of bio-digestion process was well described by modified Gompertz model and the experimental and predicted values of biogas production were fitted well with correlation coefficient values > 0.96 suggesting favorable conditions of the process.

Key Words: biogas, anaerobic digestion, lignocellulosic waste, clean energy.

استخلاص الغاز الحيوي من الهضم اللاهوائي المشترك لمخلفات الدواجن لانتاج الطاقة النظيفة

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الخلاصة

تعد عمليات الهضم اللاهوائي من اكثرالتقنيات استخداما لمعالجةِ النفايات العضويةِ لاغراض انتاجِ الغاز الحيوي كمصدر للطاقةِ النظيفةِ. في هذه الدراسة تم استخدام مخلفات الدواجن كمصدر لانتاج غاز الميثان حيث تم دراسة تأثيرات بعض العوامل التشغيلية كأضافةِ براز الحيوانات (تحديدا الدجاج)، المعالجة الكيمياوية التمهيدية للمخلفات قبل اجراء عملية الهضم اللاهوائي، و درجة حرارة على إنتاجِ الغاز الحيوي. بينت النَتائِجَ بأنّ تأثيرَ إضافةِ براز الحيوانات كَانَ أكبر من تأثير المعالجةِ التمهيدية القلويةِ للفضلاتِ الخامِ. الغازَ الناتج مِنْ المخلفات بعد اضافة براز الحيوانات اكثرُ من الغاز الناتج مِنْ المخلفات بدون اضافة بما يقارب 70% تحت ضروف الحرارة المعتدلة (Mesophilic). اما الغاز الناتج مِنْ المخلفات التي تمت معالجتها بشكل اولي فقد كان معدلُ انتاجه اعلى من المخلفات التي بدون معالجة تمهيدية بما يقارب 20% تحت ظروف حرارة معتدلة (Mesophilic) اما في الظروف الحرارية الاعلى (Thermophilic) فقد بينت النتائج ان كميات الغاز الحيوي الناتج قد ارتفعت الى 73%. تم تطبيق نموذج رياضي لعملية الهضم وهو (Modified Gompertz Model) على القيم الناتجة من التجارب المختبرية, وقد بينت النتائج وجود تطابق بين النتائج المختبرية والنظرية بمعامل ارتباط > 0.96.

الكلمات الرئيسية : الغاز الحيوي، الهضم اللاهوائي، المخلفات اللكنوسيليلوزية، الطاقة النظيفة.

1. INTRODUCTION

Renewable energy is a socially and politically defined category of energy sources. Renewable energy is generally defined as energy that comes from resources which are continually replenished on a human timescale such as sunlight, wind, rain, tides, waves and geothermal heat. About 16% of global final energy consumption comes from renewable resources, with 10% of all energy from traditional biomass, mainly used for heating, and 3.4% from hydroelectricity. Renewable energy sources play a key role in the current European Union strategies to mitigate the impact of global warming. Among the different forms of renewable sources, biomass is undoubtedly one of the most promising**, Messineo, et al., 2012.** When biomass is burn or digested, the emitted CO_2 is recycled into the atmosphere, so not adding to atmospheric CO_2 concentration over the lifetime of the biomass growth, **Twidell,** and **Weir, 2006.**

Anaerobic digestion has been, and continues to be, one of the most widely used processed for the stabilization of biosolid waste, such as from the agro and municipal waste to industrial waste. The widespread use of this technology stems from its potential advantages. These advantages include the production of energy of methane (in excess of that required for process operation), a reduction of 30–50% of waste volume requiring ultimate disposal, and a rate of pathogen destruction-particularly in the thermophilic process. The anaerobic digestion technology, properly implemented in an agro, municipal or industrial technical reality, can also be used to control malodorus emissions. The stabilized biomass can also be utilized as an excellent soil conditioner after appropriate treatment**, Converti, et al., 1999.**

Biogas is a gas mixture mainly composed of methane. The composition of biogas varies depending upon the types and relative contents of different raw materials, as well as upon the different conditions and fermenting phases. The quality of biogas generated by organic waste materials does not remain constant but varies with the period of digestion**, Abdel-Hadi, 2008.**

Yunqin, et al., 2009 developed an alkali pretreatment process prior to anaerobic digestion of pulp and paper sludge (PPS) to improve the methane productivity. Different concentrations of sodium hydroxide solution were used to pre-treat the pulp and paper sludge (PPS). The process efficiency of PPS with and without pretreatment was evaluated. The highest methane yield under optimal pretreatment condition was $0.32m^3$ CH_4/kg VS removal. The results indicated that alkali/NaOH pretreatment could be an effective method for improving methane yield with PPS.

Kafle, et al., 2013, studied the use of fish waste (FW) obtained from a fish processor for biogas production. The FW silages were prepared by mixing FW with bread waste (BW) and brewery grain waste (BGW), and the quality of the prepared silages were evaluated. A first-order kinetic model and the modified Gompertz model were used to predict methane yield. The biogas and methane yield for FW silages after 96 days was calculated to be 671–763 mL/g VS and 441–482 mL/g VS, respectively.

Current study, aimed to study the biogas production and recovery from the anaerobic co-digestion of poultry house wastes. This type of solid waste materials is abundantly available in Iraq without proper consideration and management.

2. MATERIALS AND METHODS

2.1 Materials

Poultry houses wastes (PHW) used in this study included a mixture of chicken feather, chicken feet, egg cartons and boxboard. Samples were freshly collected from local poultry houses. These materials are available in enormous quantities as a discarded waste material of no economic value. Inoculum, chicken dung which is known to be rich in methanogenic anaerobic bacteria was used to inoculate the bio-digesters. These materials were freshly collected from local slaughter and poultry houses, prepared as slurry, and then added to the digesters as a supplementary material to enrich the bacterial activity and enhance the anaerobic bio-digestion process. All chemical reagents used in this study were of analytical grade as given in **Table 1.**

2.2 Methods of Analysis

2.2.1 Total, volatile solids and pH

The measurement of total solids (TS) and volatile solids (VS) were carried out in triplicate according to the procedure outlined in the *standard met*hods**, APHA, 1998.** pH was measured using pH meter (Model: WTW, Inolab 720). The average measured values of total solids (TS), volatile solids (VS), and pH for the examined poultry house waste samples were found to be 24.28 ± 1.20, 23.32 ± 1.08, and 7 ± 0.4, respectively.

2.2.2 Biogas production

The produced biogas was measured by three different methods including the followings:

Manometer, a simple apparatus consisted of glass U-tube shape with 10 mm internal diameter filled with potassium hydroxide solution. The U-tube hitched with tap to adjust the level of solution with atmospheric pressure after CO_2 removal. The tube was provided with two ports, one for a biogas injection, and the other for gas outlet after removal of CO_2. Methane percentage was measured using potassium hydroxide solution in the laboratory scale investigation. The released gas was fractioned in a percentage (i.e. methane and CO_2 percentage) using the 4% potassium hydroxide. All measurements were carried out at room temperature and atmospheric pressure. The volume of gases was recalculated for standard temperature and pressure (STP: 0^oC and 1 bar)**, Hansen, et al., 2004**.

Water displacement method, the gases were first passed through an airtight washing bottle containing 1 molar sodium hydroxide solution in order to eliminate the carbon dioxide. Then the remaining methane passed to a 500-ml glass container; displacing the water which overflowed into a measuring cylinder. The volume of displaced colored water represents the volume of produced methane.

Gas chromatography (GC), was used to determine the major components of the biogas produced as a byproduct of the anaerobic digestion process.

2.3 Experimental Procedure

The experimental work consisted of the main following steps:

Pretreatment of waste materials, the pretreatment of poultry house wastes was carried out to facilitate the hydrolysis of cellulose component existing in the substrate. Cellulose has a highly crystalline structure due to the presence of an extensive hydrogen bond and inter-chain in the cellulose structure. There are various methods of pretreatment to destruct the lignin component and to reduce the crystalline nature of the cellulose structure. After manual cleaning by removing dirt dust, the clean materials were crushed, and sieved to different particle sizes. Chemical pretreatment included the addition of $Ca(OH)_2$ to the sieved waste materials at concentrations ranged from 0.1 to 0.2 g $Ca(OH)_2$/g TS of waste was carried out then the mixtures were autoclaved at 120 °C for 20 min. The calcium will precipitate and removed as $CaCO_3$ by flushing the autoclaved mix with CO_2, **Forgács, 2012**.

Inoculum preparation, Inoculum slurry was prepared by mixing either 50 g of chicken dung with 400 mL distilled water. The mixed slurry was manually homogenized with glass rod.

Experimental setup and digesters start-up, in this study, a series of lab scale-digesters were operated in batch mode to study the biogas production from the poultry houses wastes. The apparatus used to carry out the processes of anaerobic biological degradation, basically comprised of 500-mL Pyrex borosilicate heatproof code glass bottles act as the anaerobic bio-digesters. The components of each digester were maintained at 1:10 which is equivalent to 40 g solid waste material: 400 mL (inoculum slurry or distilled water). Each digester was tightly plugged with rubber stopper contains 2 holes each of 4mm diameter through which a piece of glass tube was submersed into the digester and the other end of the glass tube was connected with rubber tube for the produced biogas transfer to the gas measuring section. The rubber stoppers were tightly wrapped with parafilm to prevent any release of the produced gas. Digesters were immersed in a thermostatic water bath to maintain the required temperature conditions. Manual shaking of digesters were daily performed to insure that substrate molecules and bacterial come into close. The experiments were divided into two groups labeled I for mesophilic tests at 38º C, and II for thermophilic tests at 55º C. Group I consisted of 3 digesters, while group II consisted of 1 digester as given in **Table 2**. To achieve anaerobic conditions in the digesters, they were flushed with nitrogen for 10 min to provide anaerobic environment conditions.

Soil fertilization with digested sludge of lignocellulosic waste materials, to examine the overall efficiency, feasibility, and sustainability of the selected treatment approach, the sludge resulted from the digestion process was further processed and a decision was made to examine the validity of utilizing this sludge as a fertilizer. Cress seeds were selected for this test. The seeds were planted in suitable pots, fertilized with the sludge. The pots were irrigated and observed on a daily basis for a period of one week.

3. RESULTS AND DISCUSSION

The results of operating 4 anaerobic bio-digesters in duplicate with (190) sample tests and measurements proved a sustainable and environmentally friendly approach for biogas recovery from the selected agro-industrial waste materials as well as reduction of the waste volume.

3.1 Biogas Production

Results of anaerobic digestion process were used to analyze the quality of biogas with respect to its major component, methane (CH_4). In order to determine the best conditions for maximum volume of the recovered biogas from the waste materials, the effect of several key parameters including inoculum addition, chemical pretreatment of the digestive waste materials, and temperature were carefully considered in this study.

3.1.1 The influence of inoculum addition

This part of work was carried out to study the effect of inoculum on biogas production. The biogas production in digester No. 1 for pretreated PHW with inoculum and digester No. 2 for pretreated PHW without inoculum was monitored for 160 day. The effect of inoculum addition on biogas yield is given in **Figs. 1-3.** However, results of the specific biogas production **Table 3** indicate that the use of inoculum improved the co-digestion process and anaerobic biodegradation of waste materials. The increase of biogas production associated with the inoculum addition is significantly related to the increase of cultures populations since the chicken dung is a rich source for bacteria. However, the existence of cellulose digestive bacteria could be another potential assumption for the increase of biogas generation rates, this type of bacteria is capable to attack the tight association between lignin and cellulose bond. These results are in a good agreement with the previously outlined findings reported by **Budiyono, et al., 2010,** for biogas production from anaerobic digestion of inoculated with rumen fluid. Results revealed that biogas production rate increased two to three times compared to the digestion of cattle manure without rumen fluid.

3.1.2 The influence of chemical treatment

This section was devoted to investigate the effect of chemical pretreatment on biogas production for each type of waste materials. Results of the chemical pretreatment effect on biogas production in digester No. 1 for pretreated inoculated PHW and digester No. 3 for untreated inoculated PHW is given in **Figs. 4-6.** Anaerobic digestion of lignocellulosic materials is a challenge because of the complex, rigid, and fibrous structure of these matters which under anaerobic conditions degrades poorly. Therefore, the addition of alkaline buffer based on total solid contents increased the biodegradability of the organic fraction of solid waste, **Abdulkarim,** and **Evuti, 2010**. However, plots given in **Figs. 4-6** indicate that the effect of alkaline pretreatment for this waste material was significant with respect to the enhancement of co-digestion process and the subsequent biogas production. **Table 4** presents the effect of pretreatment on the biogas produced from the co-digestion process of the lignocellulosic waste materials in this study.

3.1.3 The influence of temperature

Results revealed a significant effect of temperature on biogas production as given in **Fig. 7**. The biogas recovery at thermophilic conditions was relatively higher than at mesophilic conditions in all digesters. This is due to the general rule that temperature is a very important operational parameter in anaerobic digestion processes. **Zinder, et al., 1984,** suggested that methanogensis are optimal at 55 to 60°C and completely inhibited at 65°C. **Table 5** summarizes the effect of temperature condition on the specific biogas production during 90 days-period observation indicating that biogas production at thermophilic conditions exceeds its production at mesophilic conditions by 73%. In conclusion, biogas yield with respect to methane content produced at thermophilic conditions is more favorable than its quality produced at mesophilic temperature range in this study **Fig. 8**. These observations are in a good agreement with the previously reported data regarding the biogas production at mesophilic and thermophilic conditions. **Vindis, et al, 2009,** reported a decrease in solid retention time and increase in biogas production from anaerobic digestion of maize silage under thermophilic conditions. **Achu,** and **Liu, 2010,** realized higher biogas productivity under thermophilic conditions.

3.2 Kinetic Model

Biogas production rate in batch condition is corresponding to specific growth rate of methanogenic bacteria in the bio-digester. Accordingly, the predicted biogas production rate will obey Modified Gompertz Model Eq. (1)**, Nopharatana, et al., 2007,** as follows:

$$G_{(t)} = G_0 . exp\{- exp\ [\ ((R_{max} . e)/G_0)\ (\lambda - t) + 1\ ]\} \tag{1}$$

Where:

$G_{(t)}$ = the cumulative biogas yield at a digestion time (mL/g VS)
G_0 = the biogas potential of the substrate (mL/g VS)
R_{max} = maximum methane production rate (mL/g VS-d)
λ = lag phase (day)
t = time (day)
e = exp (1) = 2.7183.

A nonlinear least-square regression analysis was performed using SPSS [IBM SPSS statistics 18 (2009)] to determine λ, R_{max}, and the predicted biogas and methane yield **Table 6** at 90 day. Plots of the measured and predicted values of biogas production are given in **Figs. 9-11**. It is well observed that the predicted values of biogas production using modified Gompertz model is well fitted with the measured values. Results of this section are in a good agreement with the previously outlined findings. **Kafle, et al., 2013,** reported that the measured values of biogas produced from the bio-digestion of fish waste are well fitted with the predicted values using modified Gompertz model. **Budiyono, et al., 2010,** proved that the measured values of biogas produced from the digestion of cattle manure in batch mode are well fitted with the predicted data obtained by modified Gompertz model.

3.3 Soil Fertilization with Residual Digestates

The results of this part of work demonstrated that the selected process is a potential approach to treat residues of digestion process of poultry house waste materials. **Fig. 12** presents the growth progress of cress seeds after one week's observation period. As shown in this Figure, healthy favorable growth of fertilized crop was observed compared to the non-fertilized crop indicating that this approach is potential method to treat residues of digestive process.

4. CONCLUSIONS

This study was devoted to investigate the potential of anaerobic co-digestion for biogas production using abundantly available lignocellulosic waste materials of no economic value as the substrate. The co-digestion process was evaluated using poultry houses wastes (PHW). The main conclusions that can be drawn from this study are as follows:

● The experimental work demonstrated that the volume of produced biogas significantly affected by inoculum addition, pretreatment of waste materials, temperature conditions (mesophilic or thermophilic).

● The ultimate biogas yield from co-digesting of inoculated wastes was estimated to be 99.058 ± 3.8 mL/g VS, whereby without waste inoculation it was 58.261 ± 4.7 mL/g VS for PHW. These results indicate the potential effect of inoculum addition on the digestion process.

● Maximum biogas production from co-digestion of alkaline pretreated wastes was estimated to be 99.058 ± 3.8 mL/g VS, whereby, it was 82.246 ± 6.3 mL/g VS for untreated PHW.

● During 90 days observation period, maximum biogas production from pretreated inoculated PHW were 87.173 mL/g VS at mesophilic temperature condition. However, higher rate of methane production was observed at thermophilic condition which were 150.870 mL/g VS.

● kinetic of bio-digestion process was well described by Modified Gompertz Model and the experimental and predicted values of biogas production were fitted well with correlation coefficient values > 0.96 for the PHW suggesting favorable conditions of the process.

REFERENCES

- Abdel-Hadi, M.A., 2008, *A Simple Apparatus For Biogas Quality Determination,* Misr Journal Agriculture Engineering, Vol.25, PP. 1055- 1066.

- Abdulkarim, B.I., Evuti, A. M., 2010, *Effect of Buffer (Nahco$_3$) and Waste Type in High Solid Thermophilic Anaerobic Digestion*, International Journal of ChemTech Research, Vol. 2, PP. 980-984.

- Achu N.I., Liu, J., 2010, *Effects of Solid Retention Time on Anaerobic Digestion of Dewatered-Sewage Sludge in Mesophilic and Thermophilic Conditions*, Renewable Energy, Vol. 35, PP. 2200-2206.

- American Public Health Association (APHA), 1998, Standard methods of the examination of water and wastewater, Washington, DC.

- Budiyono, I N. Widiasa, S. Johari, and Sunarso, 2010, *The Kinetic of Biogas Production Rate from Cattle Manure in Batch Mode*, International Journal of Chemical and Biological Engineering, Vol. 3, PP. 39–44.

- Converti, A., Del Borghi, A., Zilli, M., Arnì, S., Del Borghi, M., 1999, *Anaerobic Digestion of the Vegetable Fraction of Municipal Refuses: Mesophilic Versus Thermophilic Conditions*, Bioprocess Engineering, Vol. 21, PP. 371–376.

- Forgács, G., 2012, *Biogas Production from Citrus Wastes and Chicken Feather: Pretreatment and Co-digestion*, PhD Thesis, Borås University.

- Hansen, T. L., Schmidt, J. E. Angelidaki, I., Marca, E., Jansen, J., Mosbaek, H., Christensen, T. H., 2004, *Method For Determination of Methane Potentials of Solid Organic Waste*, Waste Management, Vol. 24, PP. 393–400.

- Kafle, G., K., Kim, S., H., Sung, K., 2013, *Ensiling Of Fish Industry Waste For Biogas Production: A Lab Scale Evaluation of Biochemical Methane Potential (BMP) And Kinetics*, Bioresource Technology, Vol. 127, PP. 326–336.

- Messineo, A., Volpe, R., Marvuglia, A., 2012, *Ligno-Cellulosic Biomass Exploitation for Power Generation: A Case Study In Sicily*, Energy,Vol. 45, PP. 613-625.

- Nopharatana, A., P., Pullammanappallil, C.W., Clarke, P., 2007, *Kinetics and Dynamic Modeling of Batch Anaerobic Digestion Of Municipal Solid Waste In A Stirred Reactor*, Waste Management, Vol. 27, PP. 595–603.

- Twidell, J. and Weir, T., 2006, *Renewable Energy Resources*, 2nd edition, New York: Taylor & Francis.

- Vindis, P., Mursec, B., Janzekovic, M., Cus, F., 2009, *The Impact of Mesophilic And Thermophilic Anaerobic Digestion on Biogas Production*, Journal of Achievements in Materials and Manufacturing Engineering, Vol. 36, PP. 192-198.

- Yunqin, L., Dehan, W., Shaoquan, W., Chunmin, W., 2009, *Alkali Pretreatment Enhances Biogas Production in the Anaerobic Digestion of Pulp and Paper Sludge*, Journal of Hazardous Materials, Vol. 170, PP. 366–373.

- Zinder, S.H., Anguish, T., Cardwell, S. C., 1984, *Effects of Temperature on Methanogensis in a Thermophilic (58°C) Anaerobic Digestor*, Applied and Environmental Microbiology, Vol. 47, PP. 808-813.

NOMENCLATURE

$G_{(t)}$= the cumulative biogas yield at a digestion time , mL/g VS.
G_0= the biogas potential of the substrate, mL/g VS.
R_{max}= maximum methane production rate, mL/g VS-d.
λ= lag phase, day.
t= time, day.

Table 1. Chemical reagents detail.

Chemical Reagent	Chemical Formula	Purity %	Provided by	Purpose of Use
Sodium bicarbonate	$NaHCO_3$	99	BDH, England	pH adjustment
Phenolphthalein	$C_{14}H_{14}N_3NaO_3S$	99	BDH, England	To color the water in the displacement bottle
Calcium hydroxide	$Ca(OH)_2$	99	BDH, England	Pretreatment of waste
Sodium hydroxide	NaOH	98	BDH, England	CO_2 removal
Potassium hydroxide	KOH	98	BDH, England	CO_2 removal

Table 2. Digesters setup with waste material at different temperature condition.

Poultry houses waste (PHW)	Digester No.	Waste materials mix in digester	Temperature condition
Group (I)	1	Pretreated waste inoculated with chicken slurry	Mesophilic
	2	Pretreated waste with distilled water	
	3	Untreated waste inoculated with chicken slurry	
Group (II)	4	Pretreated waste inoculated with chicken slurry	Thermophilic

Table 3. Effect of inoculum addition on biogas production.

Digester No.	Inoculum	Maximum specific biogas production (mL/g VS)	Maximum specific CH_4 production (mL/g VS)	Biogas increase (%)
1	Applicable	99.058 ± 3.8	63.367	70.02
2	NA*	58.261 ± 4.7	35.932	

* Not applicable

Table 4. Effect of pretreatment process of waste materials on biogas production.

Digester No.	Pretreatment	Maximum specific biogas production (mL/g VS)	Maximum specific CH_4 Production (mL/g VS)	Biogas increase (%)
1	Applicable	99.058 ± 3.8	63.367	20.44
3	NA*	82.246 ± 6.3	51.879	

* Not applicable

Table 5. Effect of temperature on specific biogas production from pretreated inoculated PHW.

Digester No.	Temperature condition	Specific biogas production (mL/g VS)	Specific CH_4 production (mL/g VS)
1	Mesophilic	87.173	55.635
4	Thermophilic	150.870	110.225

Table 6. Results of a kinetic study using Gompertz model at mesophilic conditions.

Digester No.	$G_{(t)}$ exp. (mL CH_4/g VS)	Gompertz model parameters				R^2
		λ (day)	$R_{max.}$ (mL CH_4/g VS)	G_0 (mL CH_4/g VS)	$G_{(t)}$ model (mL CH_4/g VS)	
1	55.635	8.475	0. 877	63.367	55.830	0.981
2	32.320	18.018	0. .544	35.932	31.220	0.986
3	44.745	13.280	0. 701	51.879	44.100	0.983

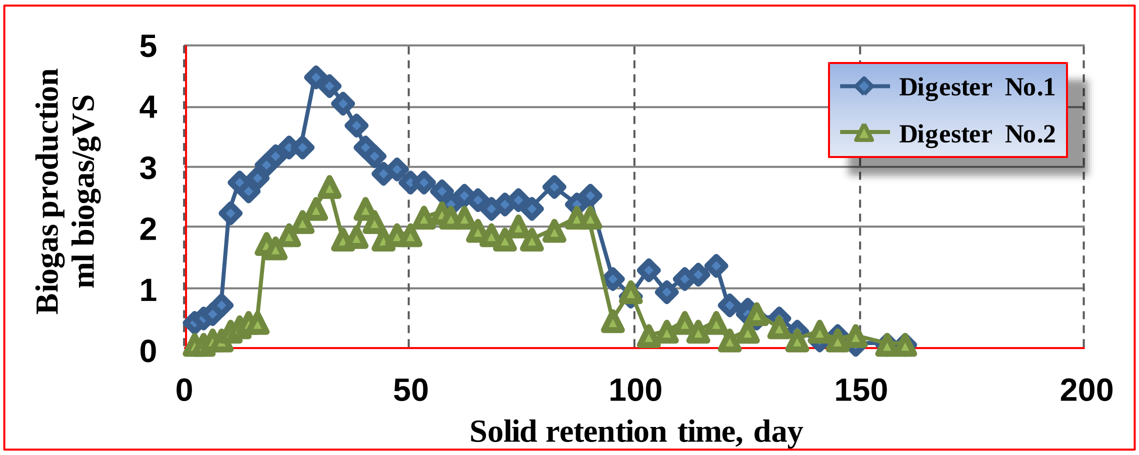

Figure 1. Biogas production profile for digesters No.1 and 2.

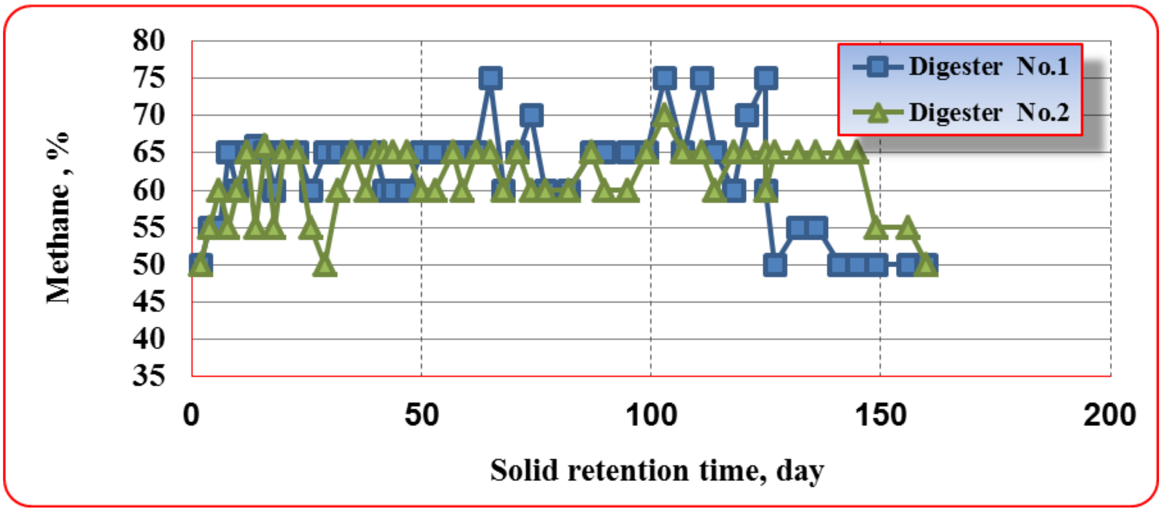

Figure 2. Percentages of CH_4 production digesters No. 1 and 2.

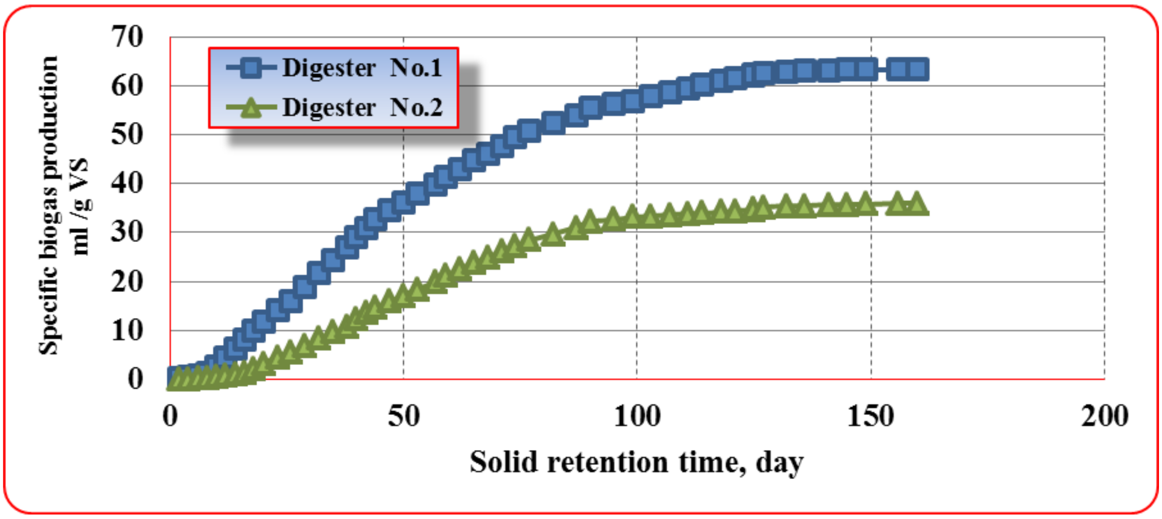

Figure 3. Specific and cumulative biogas production profiles for digesters No. 1 and 2.

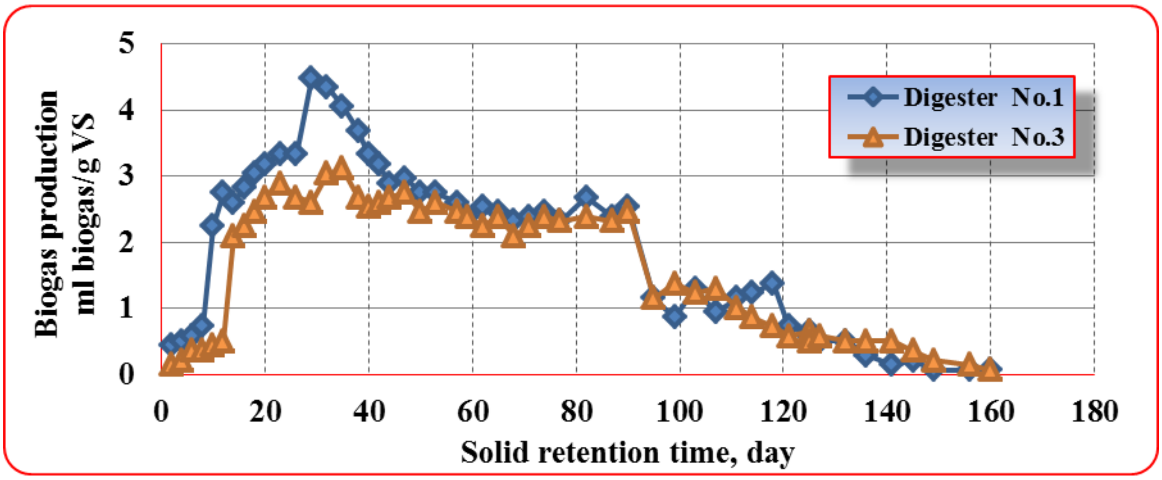

Figure 4. Biogas production profile for digesters No.1 and 3.

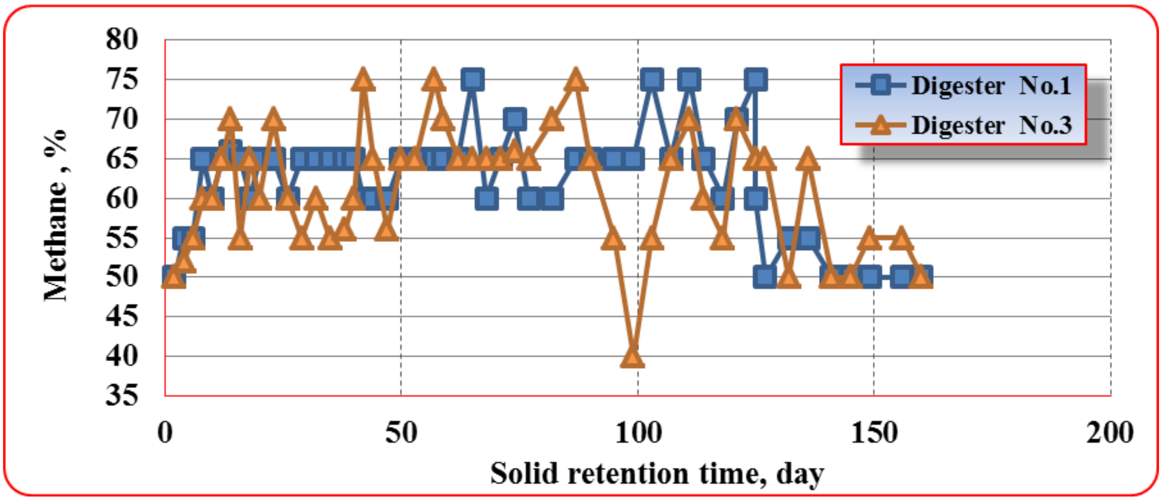

Figure 5. Percentages of CH_4 production digesters No. 1 and 3.

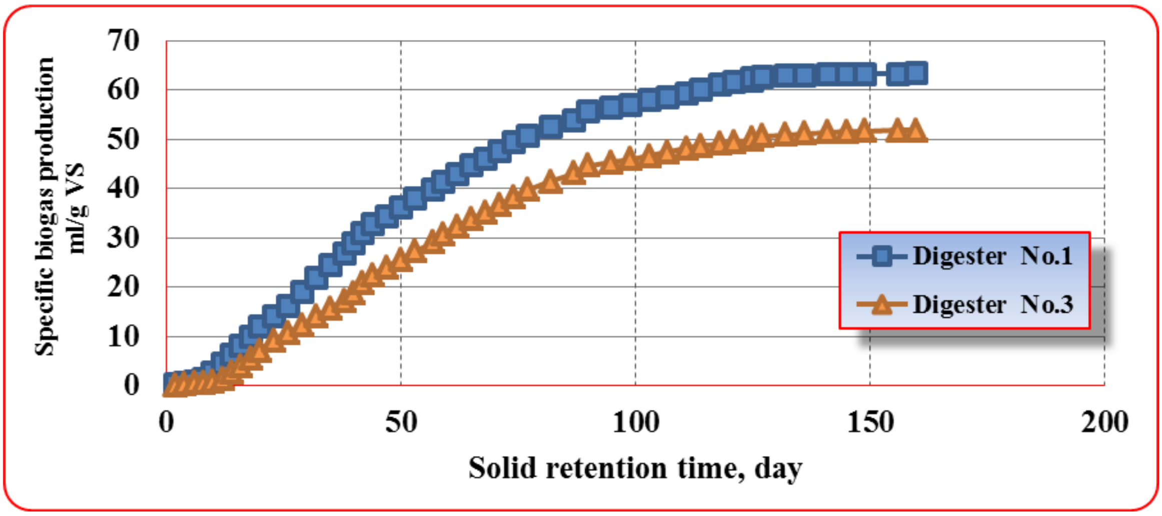

Figure 6. Specific and cumulative CH_4 production profiles for digesters No. 1 and 3.

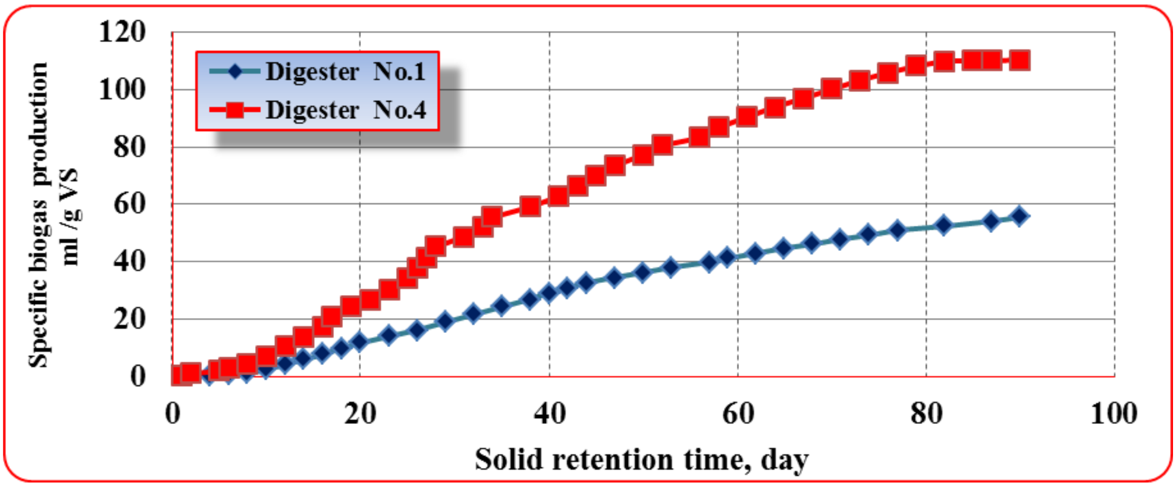

Figure 7. Specific and cumulative biogas production profiles in digesters No.1 and 4.

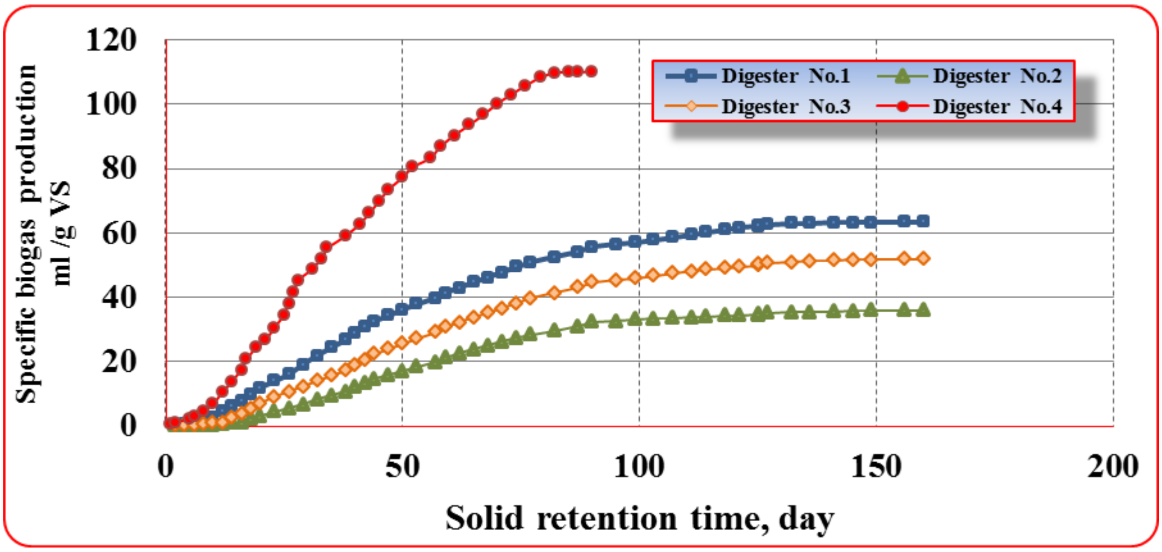

Figure 8. Potential effect of temperature on the specific biogas production for the four cases.

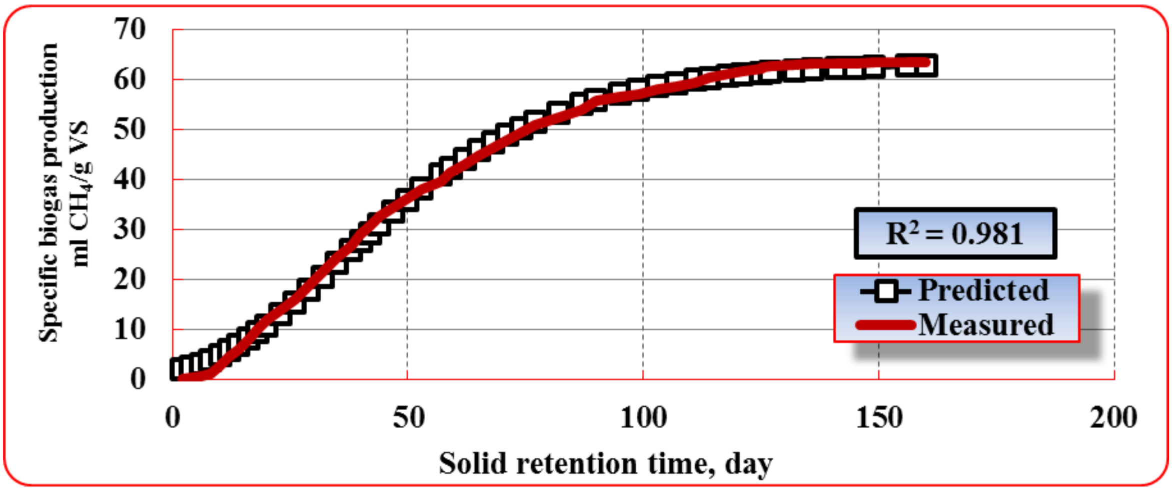

Figure 9. Measured and predicted data for pretreated inoculated PHW.

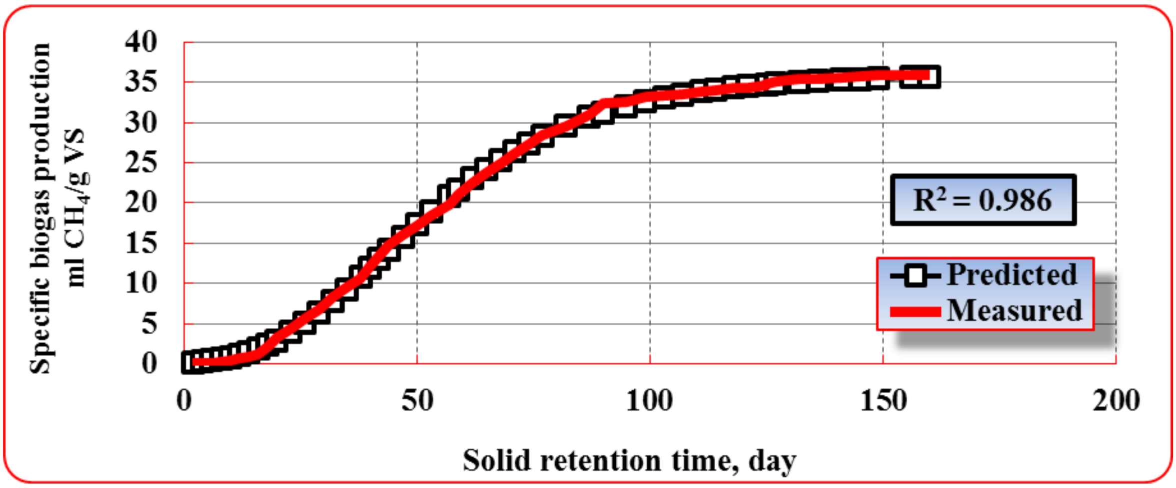

Figure 10. Measured and predicted data for pretreated PHW with distilled water.

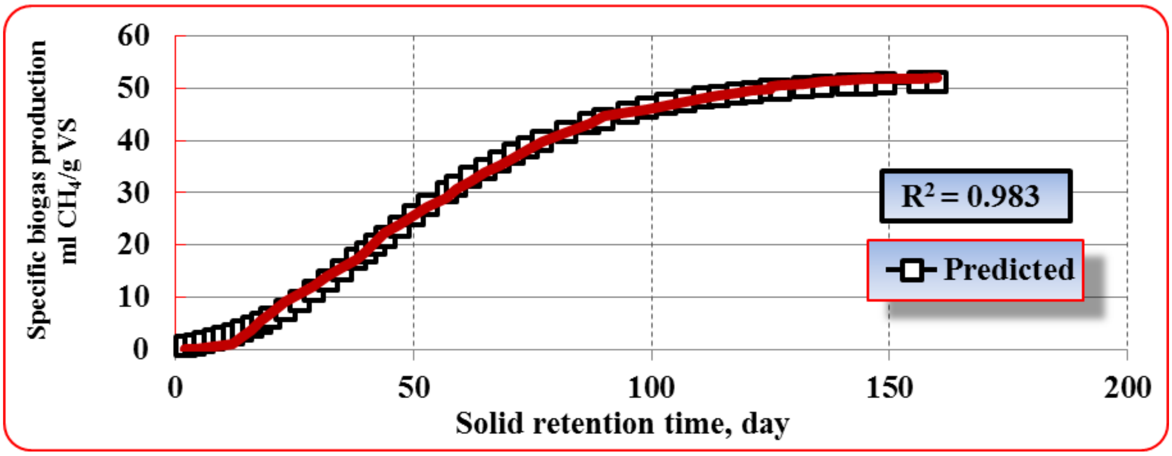

Figure 11. Measured and predicted data for untreated inoculated PHW.

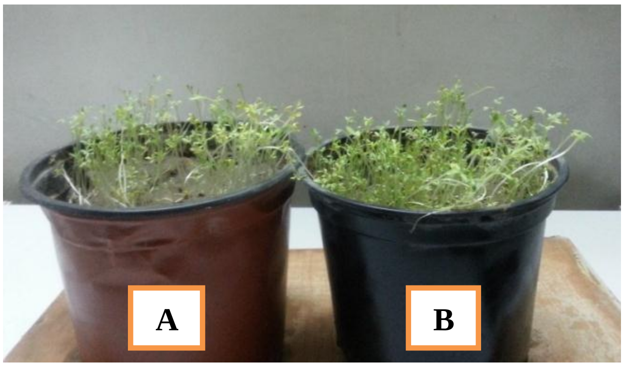

Figure 12. Growth observations for the planted cress seeds after one week, red pot (A) is for non-fertilized soil, black pot (B) for fertilized soil with digestate.