

## A Study of Upgrading Real Biogas via CO<sub>2</sub> Precipitation Route Under Indian Scenario

Avneesh Kumar Gehlaut, Ankur Gaur<sup>†</sup>, Shabih Ul Hasan and Jin-Won Park\*

Department of Chemical Engineering, Motilal Nehru National Institute of Technology, Allahabad-211004, Uttar Pradesh, India.

\*Department of Chemical and Biomolecular Engineering, Yonsei University, 50, Yonsei-ro, Seodaemun-gu, Seoul, 03722, Korea.

(Received 25 September 2017; Received in revised form 21 February 2018; accepted 8 March 2018)

**Abstract** – Our study focuses on upgrading real biogas obtained under Indian scenario using carbon capture and utilization (CCU) technology to remove carbon dioxide (CO<sub>2</sub>) and utilize it by forming metal carbonate. Amines such as monoethanolamine (MEA), diethanolamine (DEA), and sodium hydroxide (NaOH) were used to rapidly convert gaseous CO<sub>2</sub> to aqueous CO<sub>2</sub>, and BaCl<sub>2</sub> was used as an additive to react with the aqueous CO<sub>2</sub> and rapidly precipitating the aqueous CO<sub>2</sub>. All experiments were conducted at 25 °C and 1 atm. We analyzed the characteristics of the BaCO<sub>3</sub> precipitates using X-ray diffractometry (XRD), scanning electron microscopy - Energy dispersive spectroscopy (SEM-EDS) and Fourier-transform infrared spectroscopy (FT-IR) analyses. The precipitates exhibited witherite morphology confirmed by the XRD results, and FT-IR confirmed that the metal salt formed was BaCO<sub>3</sub>, and EDS showed that there were no traces of impurities present in it. The quantity of the BaCO<sub>3</sub> was larger when formed with DEA. Also, a comparison was done with a previous study of ours conducted in Korean conditions. Finally, we observed that the carbonate obtained using real biogas showed similar properties to carbonates available in the market. An economic analysis was done to show the cost effectiveness of the method employed by us.

Key words: Barium carbonate, Biogas, Precipitation, Methane, amines, Carbon dioxide

### 1. Introduction

Millions of dollars are invested in the generation of energy from the fossil fuels, and day by day fossil fuel supply is decreasing, so there is need for renewable sources of energy like biogas, wind, tidal and solar energy etc. Biogas production from waste biomass is one of the best mature renewable technologies present in the market [2-3]. Biogas generation from the waste provides two simultaneous solutions to solid waste management and energy generation, which is favored by the current Swach Bharat policy of Indian Government. Biogas is mainly produced by the anaerobic digestion of biomass. Various designs of anaerobic digesters models like fixed and floating dome type digesters are used widely, but the floating type digester has gained much attention toward biogas generation due to ease of maintenance [4]. Biogas enhancement includes removal of CO<sub>2</sub> and other impurities like hydrogen sulfide, traces of ammonia and water vapor. Carbon dioxide capture and utilization (CCU) is one of the best ways to capture the CO<sub>2</sub> produced from biogas. Absorption process is one of the most common techniques for CO<sub>2</sub> removal. In the present scenario, one of the most effective methods for the uptake of CO<sub>2</sub> is the chemical absorption process, which usually employs aqueous solutions like amines, ammonia water and adsorption. The use of amines has certain disadvantage too, like corrosion and loss of amines due to volatile nature [20]. Ammonia

water is also preferred over conventional amine absorbent due to high CO<sub>2</sub> loading [19]. Simultaneous removal of SO<sub>x</sub> and NO<sub>x</sub> along with CO<sub>2</sub> using amines makes the chemical absorption process more efficient [16]. DEA shows a higher CO<sub>2</sub> loading rate as compared to MEA [17]. A very high penalty cost is attached with the amine process for CO<sub>2</sub> capture from coal-fired plants [18]. Chemical absorption technique requires a huge amount of energy during the desorption step, which makes CO<sub>2</sub> capture uneconomical. To counter this problem, an effort was undertaken to convert CO<sub>2</sub> into solid carbonates [9]. In previous study, landfill gas was used in Korean conditions and CO<sub>2</sub> was successfully converted to carbonates [8-11]. This paper focuses on using a process similar to the earlier study, but the input gas is real biogas and pure CO<sub>2</sub>. We have considered the Indian scenario instead of landfill gas. The data obtained during the present study is better than in the previous study [9]. The amount of carbonates formed is higher. Previous study [9] was just a technical note, so some technical and economic data are not mentioned. However, in the current study technical data such as biogas production rate, characterization of carbonates formed using techniques such as FTIR, XRD and SEM-EDX is covered. Also, economic analysis was done to show how converting CO<sub>2</sub> to carbonate makes the traditional CO<sub>2</sub> capture process profitable, which has not been discussed in literature till date. This technique really suits the Indian scenario and can make biogas plants a profitable venture.

### 2. Experimental

#### 2-1. Materials

All the chemicals, such as MEA, DEA and NaOH, were pur-

<sup>†</sup>To whom correspondence should be addressed.

E-mail: ankur@mnnit.ac.in

This is an Open-Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/3.0>) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

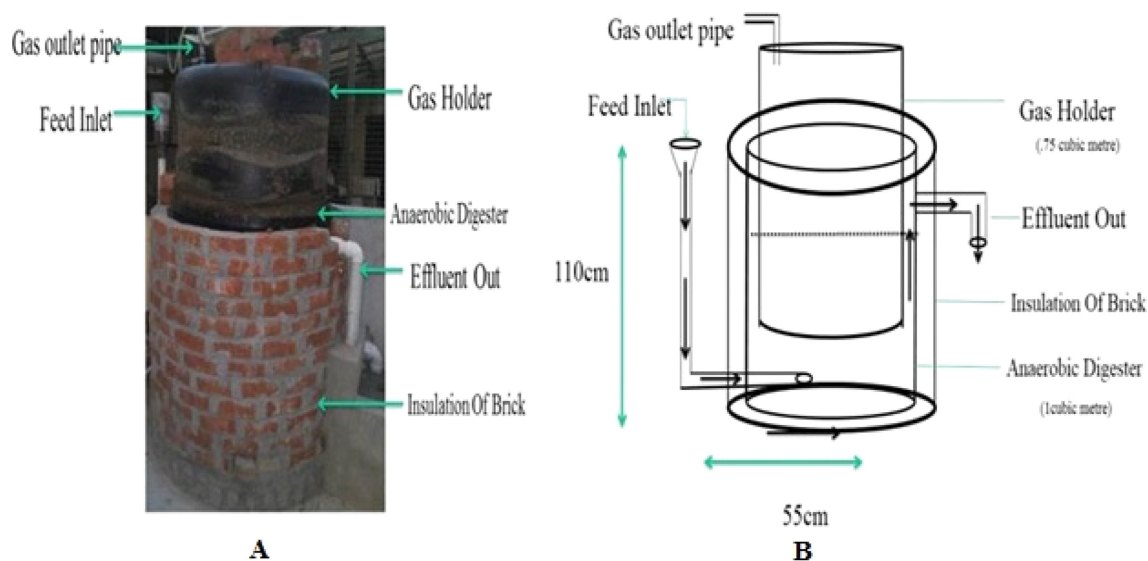


Fig. 1. A. Anaerobic digester setup used during this study B. Exact dimensions of anaerobic digester.

chased from CDH (purity: >99%). Deionized water was used for solution preparation. All chemicals were of analytical grade and used as received without further purification. Fresh cow dung and water were obtained from the Narayani Ashram, Allahabad.

## 2-2. Absorption of CO<sub>2</sub>

In the precipitation experiment we used 50 grams of BaCl<sub>2</sub> dissolved in water with additives like amines and NaOH. The first step involved saturation of the amine and BaCl<sub>2</sub> solution with biogas and pure CO<sub>2</sub> gas. Each amine was diluted to a different concentration with balance deionized water. The CO<sub>2</sub> absorption reactor was filled with 1 Liter solution of BaCl<sub>2</sub> and amines. We maintained the temperature at 25° C and 1 atm pressure. The biogas was passed into the absorption reactor and outlet/inlet gas was evaluated using CO<sub>2</sub> ana-

lyzer of different intervals after reacting with the amine solution. The entire process was conducted for 1 h. Then, we separated the liquid and solid by filtration through filter paper. In addition, we used gas chromatography to measure the initial and final biogas composition.

The reactions of primary and secondary amines with CO<sub>2</sub>

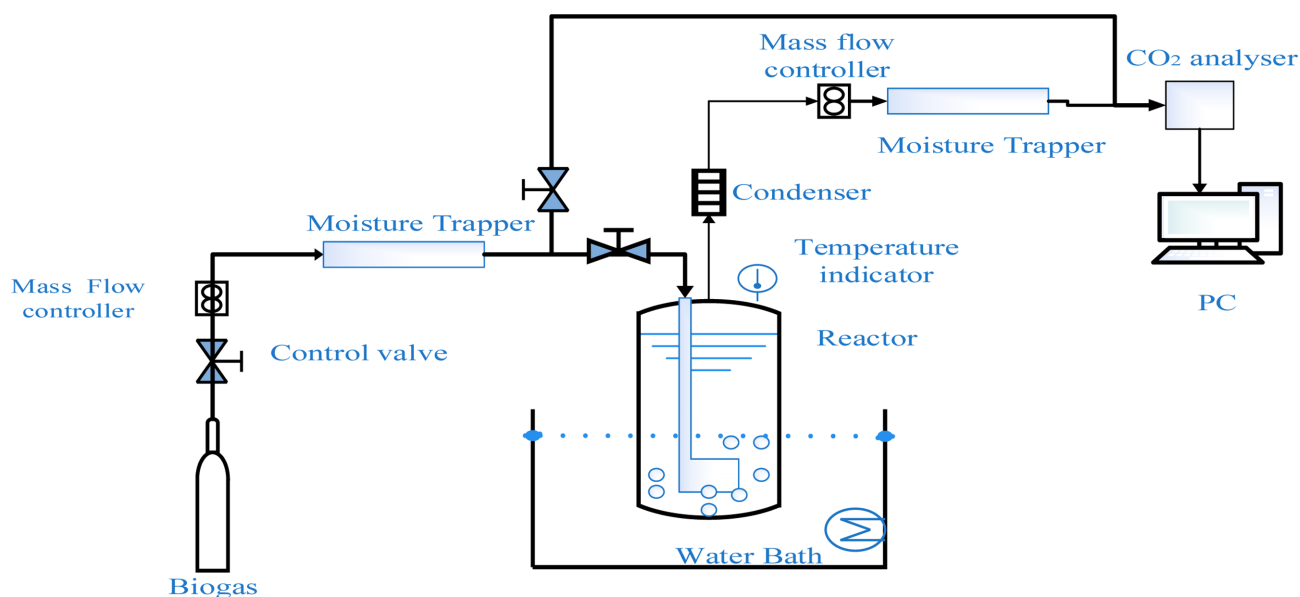
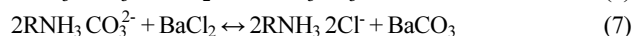
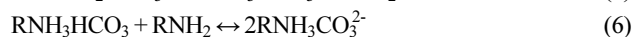
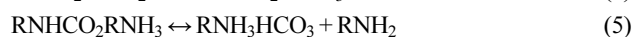
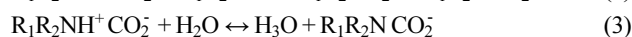
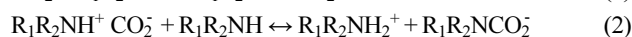


Fig. 2. Schematic diagram of carbonation experimental apparatus.

### 2-3. Physical Characterization

The X-ray diffraction (XRD) patterns of the BaCO<sub>3</sub> were recorded with Rigaku D/MAX-2400X-ray diffractometer system using a Cu K $\alpha$  radiation ( $1\frac{1}{4}$  1.5406 Å) in the 2 $\theta$  range from 5° to 65°, operated at 40 mA and 40 kV, and a scanning speed of 10° Min<sup>-1</sup>. The FT-IR spectra were measured on an ATR FTIR spectrophotometer into the sample cell with a thickness of 0.005 mm between two KBr plates in the range of 4000- 400 cm<sup>-1</sup>. Surface morphology of the BaCO<sub>3</sub> was analyzed using CARL ZEISS EVO 50 with resolution - 2.0 nm at 30 kV, acceleration Voltage-0.2 to 30 kV, magnification-5x to 1,000,000x, field of view-8.5 mm at the analytical working distance (AWD), X-ray analysis 8.5 mm AWD and 35° take-off angle; detectors used were SE in HV - Everhart-Thornley and BSD in all modes - quadrant semiconductor diode.

## 3. Results and Discussion

### 3-1. Biogas Production

The biogas was obtained from a real biogas plant situated in Narayani Ashram near our University. The photograph and dimensions of the real biogas plant are in Fig. 1. The gas holder volume was 0.75 m<sup>3</sup>; brick insulation of around 10 cm was done around anaerobic digester to maintain the temperature. The feed rate was around 5 kg per day. Biogas was produced from cow dung over a period of 29 days and it increased gradually as mentioned in Fig. 3. Biogas production increased progressively after the 16<sup>th</sup> day. The biogas was analyzed using GC and it was mainly composed of CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>S, water vapor and ammonia. The components of biogas are mentioned in Table 1. Methane was present in the range 55-65 volume %. CO<sub>2</sub> was present in the range 35-40%, and rest of the components were less than 5%. Our analysis matched the references [5-7] as discussed in Table 2. We used high quality silica gel before the biogas entered the reactor. Silica gel effectively removed all the minor components present in the biogas. The biogas entering into the reactor mainly consisted of methane CH<sub>4</sub> and CO<sub>2</sub>. The Indian subcontinent provides the ideal temperature for high quality methane production.

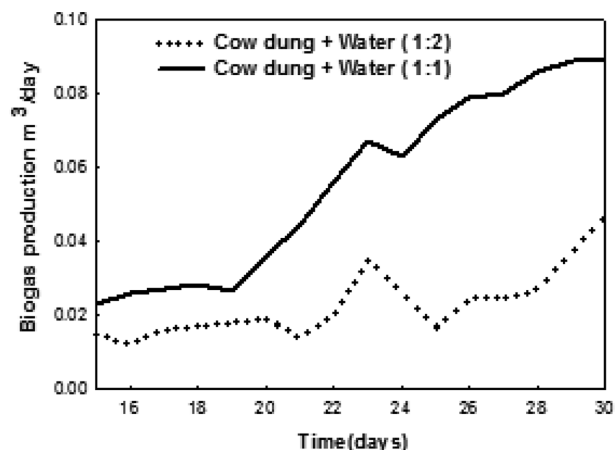
It was observed that the digester temperature fluctuated between 28 °C and 35 °C while the pH of the medium was between 6.5-7.2. In the anaerobic digestion the pH initially decreased to 6.6, and after the

**Table 1. Concentration of main components present in biogas**

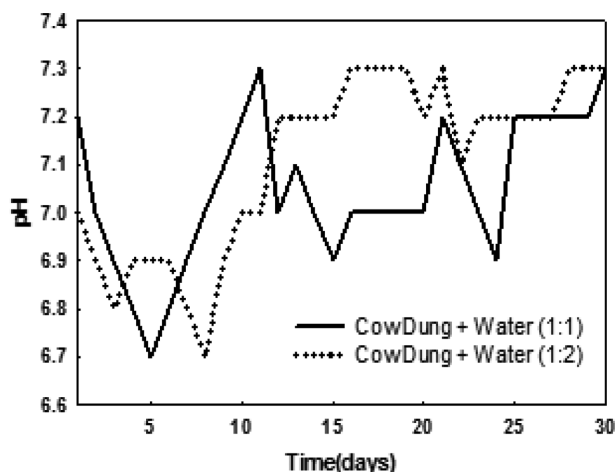
Main Components	% content (% vol) Current study		Ref.
Methane (CH <sub>4</sub> )	55-65	55-70	[5]
Carbon Dioxide (CO <sub>2</sub> )	35-40	30-40	[5]
Hydrogen Sulfide (H <sub>2</sub> S)/ water vapor/Ammonia	0-5	0-5	[5]

**Table 2. Comparison of parameters measured in anaerobic digester**

Parameters	Current study		Ref.
VFA	240-350	350-550	[5-7]
pH	6.8-7.4	6.8-7.4	[5-7]
Temperature	25-45 °C	0-35 °C	[5-7]



**Fig. 3. Variation in biogas production using different ratio of cow-dung and water.**



**Fig. 4. Change in pH with respect to time (days) in anaerobic digester.**

thirteenth day pH was around 7, as displayed in Fig. 4. In biogas generation, pH plays a vital role; if pH is decreased beyond 6 then no biogas is generated. The range of temperature and pH matched the reference data [5-7], as mentioned in Table 2.

Methanogens produce methane as a metabolic by-product in anaerobic conditions. They uniquely belong to the archaea kingdom, which are very pH sensitive, so it is mandatory to maintain the pH around 7 and temperature above 25 °C.

Volatile fatty acid (VFA) also plays a vital role in gas production; as we can observe from Fig. 5 that cow-dung in 1:1 ratio mixtures with water gives a high VFA as compared to cow dung 1:2 ratio mixture. The VFA value obtained by us matched the VFA in references which used cow dung as a feed as mentioned in Table 2.

### 3-2. Carbonate formation

There are nine different types of prepared solutions which are marked as A, B, C, D, E, F, G, H and I. Solutions A, B and C consist of 1, 2 and 3 wt% NaOH, respectively; solutions D, E and F consist of 1, 2 and 3 wt% MEA, respectively; solutions G, H and I consist of 1, 2 and 3 wt% DEA, respectively. The pH of the final solution set-

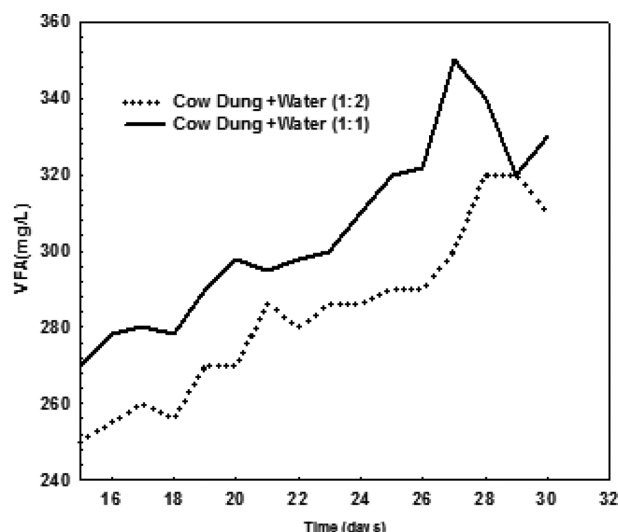


Fig. 5. Variation in between VFA and Time (days) for different ratio of cow dung and water.

Table 3. Change in pH of different solutions before and after passing biogas

Solutions	Initial pH	Final pH
1 wt% NaOH + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (A)	12.89	7.93
2 wt% NaOH + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (B)	12.50	7.86
3 wt% NaOH + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (C)	12.10	7.62
1 wt% MEA + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (D)	12.82	7.52
2 wt% MEA + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (E)	12.03	7.13
3 wt% MEA + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (F)	11.16	7.16
1 wt% DEA + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (G)	13.20	7.80
2 wt% DEA + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (H)	12.72	7.60
3 wt% DEA + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (I)	12.03	7.03

tioned between 7~8 as mentioned in Table 3. Taking a cue from our previous work [9], we decided to take 50 g of Barium salt.

The amount of carbonates obtained from the alkaline solution is also displayed in increasing order D<G<A<E<H<F<B<I<C. In

Table 4. Amount of carbonates formed using biogas and pure CO<sub>2</sub>

Solutions	Amount of carbonates formed (g[sorbent L] <sup>-1</sup> ) (biogas)	Amount of carbonates formed (g[sorbent L] <sup>-1</sup> ) (pure CO <sub>2</sub> )
1 wt% NaOH + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (A)	22.3	30
2 wt% NaOH + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (B)	36.6	40
3 wt% NaOH + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (C)	48.8	54.8
1 wt MEA + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (D)	12.7	24.1
2 wt% MEA + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (E)	26.2	34.2
3 wt% MEA + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (F)	36.3	43.2
1 wt% DEA + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (G)	16.6	24.7
2 wt% DEA + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (H)	28	36.1
3 wt% DEA + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (I)	39	45.6

Table 5. Comparison of current work with [9]

Solutions	Amount of carbonates formed (g[sorbent L] <sup>-1</sup> ) (Biogas)	Amount of carbonates formed (g[sorbent L] <sup>-1</sup> ) (pure CO <sub>2</sub> )	[9] (g[sorbent L] <sup>-1</sup> ) (Landfill Gas)
5 wt% NaOH + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (J)	49	56	NA
5 wt% MEA + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (K)	40	48	34
5 wt% DEA + 50g BaCl <sub>2</sub> ·2H <sub>2</sub> O (L)	42	49.2	35.90

Table 4 the amount of carbonate formed is displayed. Most of the solutions were neutralized after the precipitation reaction was over. We can also observe in Table 5 that quantity of carbonates obtained during the current study is higher than in the previous study.

### 3-3. FTIR

FTIR characterization of the precipitated BaCO<sub>3</sub> obtained by the absorption of CO<sub>2</sub> was done. The result of the FTIR graph is shown in Fig. 6. The spectra are similar to the spectrum of pure BaCO<sub>3</sub> which presents peaks primarily at  $k = 1428, 878$  and  $736$  cm.

The BaCO<sub>3</sub> salt obtained from pure CO<sub>2</sub> and biogas showed increased absorbance at higher concentration, which was similar to characteristics of pure BaCO<sub>3</sub>. Similar peak was observed in [13]. Both the FTIR results showed that there is not much difference in property of barium carbonate obtained from different gas input.

### 3-4. XRD

The barium carbonate obtained using amines and BaCl<sub>2</sub> was char-

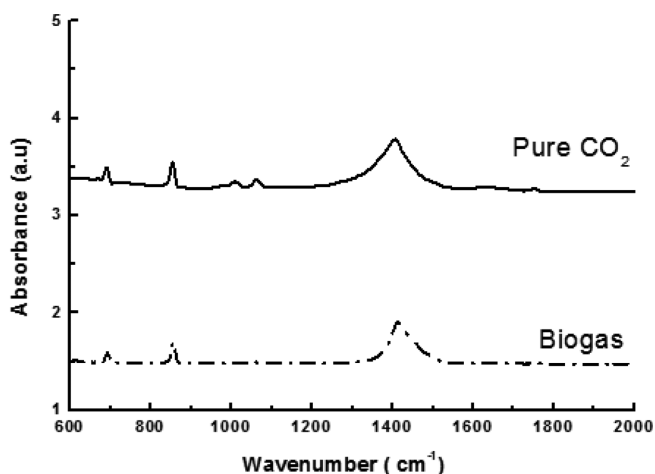


Fig. 6. FTIR of BaCO<sub>3</sub> obtained from pure CO<sub>2</sub> and biogas.

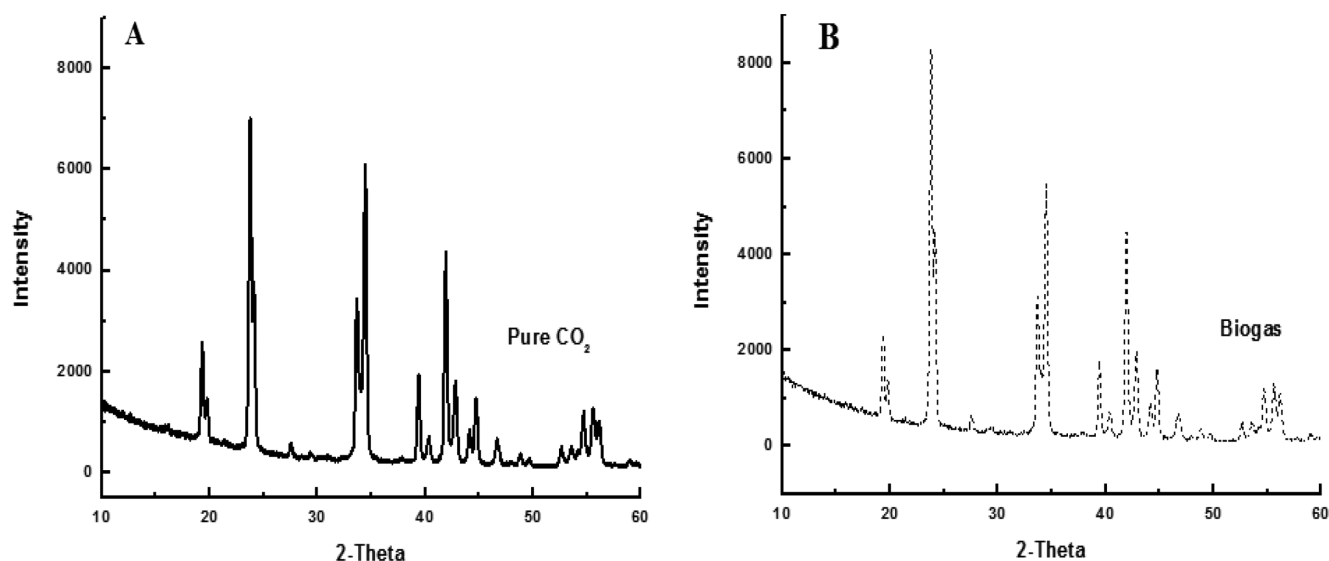


Fig. 7. XRD graph of BaCO<sub>3</sub> obtained from (A) pure CO<sub>2</sub> and (B) Biogas.

acterized by XRD to determine its crystalline phase. As far as morphology is concerned, X-ray diffraction patterns were obtained in this study as shown in Fig. 7, which matched the one numbered 41-0373 in JCPDS. From JCPDS we found that BaCO<sub>3</sub> is orthorhom-

bic and withered. We found that the different carbonate structure is derived from the amine structures.

Increase in the amine concentration resulted in greater formation of crystalline structure and more stable compound. DEA provides

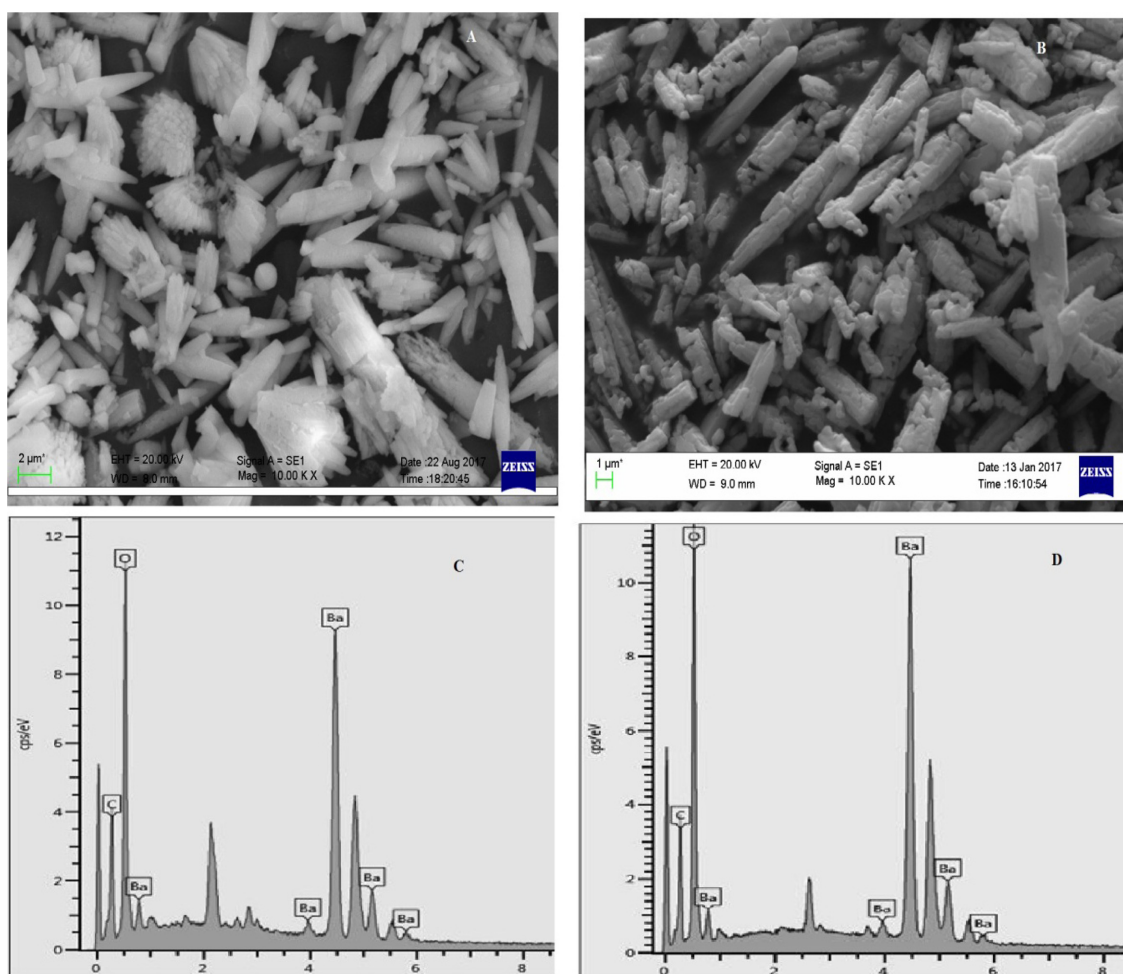


Fig. 8. A and C- SEM of Barium carbonate obtained from pure CO<sub>2</sub>, B and D EDS of Barium carbonate obtained from biogas.

**Table 6. Comparison of economics of amine and BaCO<sub>3</sub> process**

Detail of biogas plant			Unit		
No of cows			100		
Amount of cow dung			1000	kg	
Quantity of biogas produced per day			40	m <sup>3</sup>	
Amount of methane			20	kg/day	
Amount of CO <sub>2</sub>			27	kg/day	
Economical comparison					
			Amine process	BaCO <sub>3</sub> process	Unit
		Civil construction			
A.	Capital Cost	mechanical (Absorber, reactor, Heat exchanger, pumps, compressor, cylinders,	23310	15540	USD
B.	Contingency	20%	4662	3108	USD
C.	Total (Installed capital cost)		27972	18648	USD
D.	Annual O & M Expenses	Chemicals labor electricity	177156	447552	USD
E.	Total cost		205128	466200	USD
F.	Amount Of methane produced per year		7200	7200	Kg/year
G.	Price of producing 1 Kg of methane after complete removal of CO <sub>2</sub>		29	65	USD/kg methane
H.	Profit after selling methane and associated chemicals per year		11189	567831	USD
I.	Profit obtained per kg CH <sub>4</sub>		1.6	79	USD/ kg methane
J.	Effective cost of producing per kg methane		-27.4	+14	USD/ kg methane

more stable BaCO<sub>3</sub> as compared to the other amines due to more absorbance of CO<sub>2</sub> ions and precipitation of aqueous CO<sub>2</sub> in carbonate. Obtained BaCO<sub>3</sub> was also compared to the other studies done by other researchers, and we found that similar peaks were obtained [8-10]. The h,k,l value can be readily indexed as (110), (111), (002), (112), (220), (221), (132) and (113).

### 3-5. SEM-EDS of BaCO<sub>3</sub>

Fig. 8 shows the SEM micrograph of carbonate samples. BaCO<sub>3</sub> obtained from BaCl<sub>2</sub> had nanorod-like structure. As we can see, the graph obtained from the biogas provided more stable structure as compared to the pure CO<sub>2</sub>. When pure CO<sub>2</sub> was used for the reaction, it provided less nanorod-type shape structure of BaCO<sub>3</sub> [8]. In Fig. 8B the nanorods are of inferior quality as compared to Fig. 8A due to the presence of some impurities present in biogas, whereas pure CO<sub>2</sub> provides sharper rods. Our barium carbonate SEM was compared to other studies, and we found similar data when conventional method was used for barium carbonate production. Similar images were obtained by other researchers [8]. For elemental analysis of the material, further EDS was performed. No traces of impurity were present. Our micrograph and EDS confirmed that it was similar to the pure BaCO<sub>3</sub> obtained from other conventional methods. The main mineral was Ba. EDS of all samples is shown in Fig. 8. The entire spectrum shows similar elements present in the barium carbonate: barium, carbon and oxygen. It was observed that BaCO<sub>3</sub> formed by the biogas had more Barium as compared to the pure CO<sub>2</sub>. The main target of this research was to produce high quality barium carbonate which can be directly sold in the market. Nanorod BaCO<sub>3</sub> has wide range of application even in fuel cells as an alkali-earth metal-carbonate-based catalyst [14].

### 3-6. Economics

For calculating the economic feasibility of the process we considered a biogas plant which can be fed with 1000 kg cow dung every day. Most of the dairy farms in India have around 100 cows, which can generate around 1000 kg cow dung, which produces around 20 kg of CH<sub>4</sub> and 27 kg of CO<sub>2</sub>. The detailed economy comparison of MEA-based process and BaCO<sub>3</sub> process is displayed in Table 6. As we can observe from Table 6, using just amines for CO<sub>2</sub> removal is not economical as we end up paying a penalty of 27.4 USD per kg of methane produced.

Using BaCO<sub>3</sub> route we are able to make a profit of 14 USD per kg of methane produced, which makes the carbonate route an effective CO<sub>2</sub> removal technology. Detailed economic analysis will be done in future studies.

According to the Indian standard, when using methane for automotive purposes the methane content should be minimum 90%, which we can easily obtain via the BaCO<sub>3</sub> route for CO<sub>2</sub> capture.

## 4. Conclusion

Carbonation method was used in purification of real biogas using amines and BaCl<sub>2</sub>. Barium carbonate formed by the carbonation method has wide use in the glass, ceramic and paint industries. From economical point of view, this process is very reliable and cost-effective as compared to other methods. The process is extremely economical and simple to scale up. The quality of methane obtained from this process is exceedingly high quality and it can be used in numerous processes.

## References

1. Sorrell, S., Reducing Energy Demand: A Review of Issues, Chal-

- lenges and Approaches. *Renew. Sustainable Energy Rev.*, **47**, 74-82(2015).
2. Cho, J. K., Park, S. C. and Chang, H. N., "Biochemical Methane Potential and Solid State Anaerobic Digestion of Korean Food Wastes," *Bioresour. Technol.*, **52**, 245-53(1995).
  3. Bundhoo, Z. M. A., Mauthoor, S. and Mohee, R., "Potential of Biogas Production from Biomass and Waste Materials in the Small Island Developing State of Mauritius," *Renew. Sustainable Energy Rev.*, **56**, 1087-1100(2016).
  4. Bond, T. and Templeton, M. R., "History and Future of Domestic Biogas Plants in the Developing World," *Energy Sustain. Dev.*, **15**, 347-354(2011).
  5. Miah, M. R., Rahman, A. K. M. L., Akanda, M. R., Pulak, A., and Rouf, M. A., "Production of Biogas from Poultry Litter Mixed with the co-substrate Cow Dung," *J. Taibah Univ. Sci.*, **10**, 497-504(2016).
  6. Kim, D. J. and Kim, H., "Sludge Solubilization by Pre-treatment and its Effect on Methane Production and Sludge Reduction in Anaerobic Digestion," *Korean Chem. Eng. Res.*, **48**(1), 103-109(2010).
  7. El-Mashad, H. M. and Zhang, R., "Biogas Production from Codigestion of Dairy Manure and Food Waste," *Bioresour. Technol.*, **101**, 4021-4028(2010).
  8. Gaur, A., Park, J. W. and Jung, J. H., "Metal-Carbonate Formation from Ammonia Solution by Addition of Metal Salts - An Effective Method for CO<sub>2</sub> Capture from Landfill Gas (LFG)," *Fuel Process. Technol.*, **91**, 1500-1504(2010).
  9. Gaur, A., Park, J. W., Jang, H. J. and Song, H. J., "Precipitation of Barium Carbonate from Alkanolamine Solution - study of CO<sub>2</sub> Absorption from Landfill Gas (LFG), *J. Chem. Technol. Biotechnol.*, **86**, 153-156(2011).
  10. Gaur, A., Park, J. W., Jang, J. W., Maken, S., Lee, J. and Song, H. S., "Characteristics of Alkaline Wastewater Neutralization for CO<sub>2</sub> Capture from Landfill Gas (LFG)," *Energy Fuels*, **23**, 5467-73(2009).
  11. Park, S., Min, J., Lee, M. G., Jo, H. and Park, J., "Characteristics of CO<sub>2</sub> Fixation by Chemical Conversion to Carbonate Salts," *Chem. Eng. J.*, **231**, 287-93(2013).
  12. Sanna, A., Uibu, M., Caramanna, G., Kuusik, R. and Valer, M. M. V., "A Review of Mineral Carbonation Technologies to Sequester CO<sub>2</sub>," *Chem. Soc. Rev.*, **43**, 8049-80(2014).
  13. Arenas, C., Leidy, R., Manuel, F. and Martha, C., "CO<sub>2</sub> Capture via Barium Carbonate Formation After its Absorption with Ammonia in a Pilot Scale Column," *Chem. Eng. J.*, **254**, 220-229(2014).
  14. Cao, X., Hong, T., Yang, R., Tian, J., Xia, R. C., Dong, C. J. and Li, J., "Insights into the Catalytic Activity of Barium Carbonate for Oxygen Reduction Reaction," *J. Phys. Chem. C.*, **120**, 22895-902(2016).
  15. Song, H. J., Park, S., Kim, H., Gaur, A., Park, J. W. and Lee, S. W., "Carbon Dioxide Absorption Characteristics of Aqueous Amino Acid Salt Solutions," *Int. J. Greenhouse Gas Control*, **11**, 64-72(2012).
  16. Santos, S. P., Duarte, A. P., Bordado, J. C. and Gomes, J. F., "New process for Simultaneous Removal of CO<sub>2</sub>, SO<sub>x</sub> and NO<sub>x</sub>," *Ciência Tecnol. Dos Mater.*, **28**, 106-111(2016).
  17. Gomes, S., Santos, S. P. and Bordado, J. C., "Choosing Amine-based Absorbents for CO<sub>2</sub> Capture," *Environ. Technol.*, **36**, 19-25(2015).
  18. Kim, J. H., Kwak, N. S., Lee, I. Y., Jang, K. R. and Sim, J. G., "Performance and Economic Analysis of Domestic Supercritical Coal-Fired Power Plant with Post-Combustion CO<sub>2</sub> Capture Process," *Korean Chem. Eng. Res.*, **55**(3), 419-425(2017).
  19. Yoo, J. G., Park, H. S., Hong, W. H., Park, J. K. and Kim, J. N., "Effect of Precipitation on Operation Range of the CO<sub>2</sub> Capture Process using Ammonia Water Absorbent," *Korean Chem. Eng. Res.*, **45**(3), 258-263(2007).
  20. Kumar, S., Cho, J. H. and Moon, I., "Ionic Liquid-amine Blends and CO<sub>2</sub>BOLs: Prospective Solvents for Natural gas Sweetening and CO<sub>2</sub> Capture Technology - A Review," *Int. J. Greenhouse Gas Control*, **20**, 87-116(2014).