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Hydrogen sulfide removal from biogas using chemical absorption technique in packed column reactors

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ABSTRACT

The toxicity and corrosion potential of hydrogen sulfide in raw biogas underlines the need for biogas purification. Several techniques available for removal of hydrogen sulfide from biogas are out of the reach for common end users due to lack of knowledge, higher running costs, and insufficient operational skills. The present experimental study aims to propagate hydrogen sulfide removal techniques amongst the end users by using a low-cost chemical absorption technique and packed column reactors. Commercial grade chemicals like monoethanolamine, sodium hydroxide, calcium hydroxide, granular activated carbon, and steel wool were used for biogas purification in packed column reactors of 1.2 liters capacity. Hydrogen sulfide removal efficiency up to 92.41% was achievable using single purification columns. The efficiency achieved by using multiple purification column was up to 96.84%. Hydrogen sulfide removal efficiency was calculated for experimental variants like the use of a dedicated purification column, multiple purification columns, flow variations and pressure variations of raw biogas. The data for the frequency of regeneration/replacement of different chemicals was also determined. The simplicity of operation and the use of low-cost reagents in the present study can enable the use of these methods amongst end users of biogas technology for minimizing health hazards and corrosion problems.

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INTRODUCTION

Widespread use of alternative and renewable energy sources is necessary to meet the increasing energy demands of the modern world. Biogas is produced by the anaerobic digestion of diversified organic waste materials in the absence of air or oxygen. Production of biogas from waste materials fulfills the energy needs and also reduces the greenhouse gas (methane) emission into the atmosphere (Rashed and Torii, 2015). Research regarding anaerobic digestion mentions its utility as an alternative and efficient fuel technology, which offers two-fold benefits like biofuel production and sustainable waste management (Bharathiraja *et al.*, 2018). The operational aspects of the anaerobic

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digestion process include feedstock pretreatment, digestion inside the bioreactor, upgrading of the biogas and the digestate treatment (Monnet, 2003). The volume and quality of biogas produced in anaerobic digestion process depend upon parameters like digester temperature, pH of the slurry, retention time, feeding frequency and the use of catalysts for biogas generation (Sambo *et al.,* 1995); (Mandal and Mandal, 1998). Removal of carbon dioxide and hydrogen sulfide by using an appropriate technique is necessary to improve the biogas quality and make it suitable for widespread applications (Tippayawong and Thanompongchart, 2010). Removal of hydrogen sulfide from biogas is highly recommended because of the associated health hazards and also the corrosion of burners, storage tanks, and engine components (Shah and Nagarseth, 2015). The origin of hydrogen sulfide in biogas plants refers to the degradation of sulfur-containing proteins. Removal of hydrogen sulfide can take place in the digester itself or by using purification columns after the digester (Muche *et al.,* 1985). The permissible levels of hydrogen sulfide and the requirement to remove gaseous components from biogas for various applications are available from the literature. It is recommended to remove hydrogen sulfide from biogas for all the applications like the boiler, kitchen stove, stationary engines, vehicular applications or injection into the natural gas grid (Wellinger and Lindberg, 2000). Exposure to hydrogen sulfide (H_2S) causes rapid corrosion and failure of metals. Prolonged exposure to the gas causes serious health hazards in human beings. The detrimental effects on health caused by exposure to hydrogen sulfide are mentioned in the literature (Amosa *et al.,* 2010).

Techniques for hydrogen sulfide removal and earlier research achievements

Various techniques are available for removing H_2S from biogas. The selection of a technique depends upon the sulfur capture efficiency, low media and operating costs, energy prices and socio-economic policies (Abatzoglou and Boivin, 2009). In a broader perspective, H_2S removal techniques can be categorized as physical-chemical technique and the biotechnological technique. The physical-chemical methods are the traditional ones and still widely used in the market. The biotechnological techniques have found increased applications in the last two decades and have a higher efficiency than physical-chemical methods (Allegue and Hinge, 2014). The commonly used H_2S removal process can be classified as the dry oxidation process and liquid phase oxidation process. Biogas desulfurization techniques like the introduction of air/oxygen into the biogas system, adsorption using iron oxide or activated carbon, liquid phase oxidation using NaOH and $FeCl_3$ are effective for hydrogen sulfide reduction (Kapdi *et al.,* 2005). Using the catalyst iron oxide is a simplified way for hydrogen sulfide removal from biogas. Oxidized steel wool or iron chips from lathe machine are the easily available sources of iron oxide. Regeneration of iron oxide is possible by exposing it to the atmospheric oxygen. The wet technique for hydrogen sulfide removal from biogas uses sodium hydroxide, sodium carbonate, and iron oxide. Various reaction mechanisms for hydrogen sulfide removal from biogas and relevant details are available from the literature (Shah and Nagarseth, 2015). An effective method for reduction of hydrogen sulfide comprises the addition of iron chloride, iron oxide or iron hydroxide directly to the digester, or along with feed substrate in a pre-storage tank. This method is effective for lowering the H_2S fraction in biogas and needs to be operated in combination with some another H_2S removal method (Allegue and Hinge, 2014). An experimental investigation about the effectiveness of commercially available steel wool for adsorption of hydrogen sulfide (H_2S) has been made for duration of sixteen weeks. Raw biogas is passed through the polyvinyl-chloride columns filled with the steel wool. The fixed bed of regenerated steel wool could eliminate hydrogen sulfide with 95% removal efficiency (Magomnang and Villanueva, 2015). The H_2S selective absorption performance of various oxido-alkaline solutions is found to be higher than that of amine solutions. Sodium hydroxide (NaOH), monoethanolamine (MEA) and hydrogen peroxide (H_2O_2) solutions were used for capturing H_2S and CO_2 from raw biogas (Dubosis and Thomas, 2010). Oxidative scrubbing process for selective removal of hydrogen sulfide from biogas using an aqueous solution of sodium hydroxide (NaOH), sodium bicarbonate ($NaHCO_3$) and hydrogen peroxide (H_2O_2) has been

investigated in laboratory scale experiment and thereafter in industrial scale plant. The influence of pH, redox potential and solution ageing on the absorption efficiency and the consumption of chemicals were investigated (Krischan *et al.,* 2012). Methane enrichment of biogas is achieved by using calcium oxide, calcium hydroxide, and activated carbon. Biogas up-gradation profile depends on the mass of purification agent, concentration and time of the purification cycle (Rashed *et al.,* 2016). The concentration of calcium hydroxide solution and variations in biogas flow rates can affect the hydrogen sulfide removal from biogas (Mel *et al.,* 2014). Biogas purification using chemical absorption and the reagent sodalime is a cost-effective and easy-to-use method (Ghatak and Mahanta, 2016). Biogas flow rates, the type of solution used and concentration of the solution affect the biogas purification process while using calcium hydroxide and monoethanolamine for biogas purification (Srichat *et al.,* 2017). The removal of hydrogen sulfide using chemical absorption is more effective than absorption in pure water under similar conditions (Horikawa *et al.,* 2004). Chemical absorption technique requires large amount of thermal energy for solvent regeneration. For this purpose the concentrating photovoltaic/thermal hybrid system has been integrated with chemical absorption technique (Tian *et al.,* 2017). Hydrogen sulfide removal efficiency in the range of 85% to 96% is possible using a combined method of absorption and adsorption. The chemicals used for hydrogen sulfide (H_2S) removal include iron oxide (Fe_2O_3), zero valent iron (Fe^o), and iron chloride ($FeCl_2$) (Rashed and Torii, 2017). Carbon dioxide removal efficiency of 99.98% is observed by using sodium carbonate absorbent while 30% efficiency using water scrubbing method. Hydrogen sulfide removal efficiency of 70% is obtained by using sponge iron (iron oxide). Algal treatment is used for regeneration of sodium carbonate effluent from the carbon dioxide scrubber (Mohanakrishnan and Joseph, 2016). Reduction upto 72% in non-combustible elements of biogas has been achieved using a low-cost, six stage biogas filtration system. The system comprises use of water scrubber, silica gel filter, iron sponge filter, sodium hydroxide solution filter, silica gel filter and activated carbon filter for removal of carbon dioxide, hydrogen sulfide and moisture from biogas. The purified biogas has been used to operate alternating current generator with an improvement in operating efficiency (Mojica *et al.,* 2017). Chemical scrubbing of biogas gives high methane content along with reduced hydrogen sulfide content of 102 ppm and 87 ppm during two experimental variants. Steel wool (iron oxide) is used for removal of hydrogen sulfide and silica gel for moisture removal from raw biogas. Sodium hydroxide, calcium hydroxide and potassium hydroxide are used for carbon dioxide removal from biogas. The results of road testing of a vehicle fueled by purified biogas are also presented (Shah *et al.,* 2016). The present work uses floral waste as the feedstock for biogas generation. A few research papers are available which state that floral waste has a good potential for biogas generation (Alkanok *et al.,* 2014); (Ranjitha *et al.,* 2014). The floral waste needs to be given drying, mechanical and alkaline chemical pretreatment for generation of biogas (Singh and Bajpai, 2011); (Singh *et al.,* 2007). In a developing nation like India, there is a great potential for installation of biogas digesters due to abundant availability of biomass. In most of the domestic or community biogas plants biogas purification units are not used and the occupants are prone to health hazards caused by hydrogen sulfide. The techniques of biogas desulfurization are still out of reach for the majority of the common end users. The factors responsible for this phenomenon include unawareness of health hazards of hydrogen sulfide, lack of knowledge about biogas purification techniques and the cost constraints. The objective of present study is to propose low-cost and easy-to-use biogas purification techniques for the end users of biogas technology. The present study has been carried out at Pandharpur, District Solapur, Maharashtra, India in 2018.

MATERIALS AND METHODS

Biogas is generated from a fixed dome digester of 6.2 m^3 capacity using floral waste with alkaline pretreatment as the feedstock. Raw biogas from the digester contains hydrogen sulfide up to 790 ppm. Biogas to be purified is passed through the packed column reactors of 1.2 litres (L) capacity for removing hydrogen sulfide. The purification

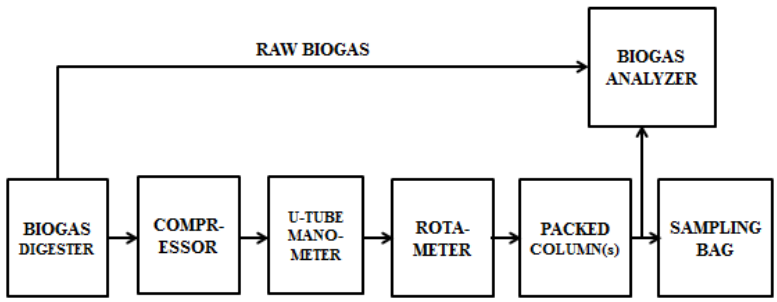


Fig. 1: Experimental set-up for biogas desulfurization

columns are filled with low-cost commercial chemicals like sodium hydroxide, calcium hydroxide, monoethanolamine (MEA), activated carbon and steel wool (iron sponge). Fig. 1 shows the schematic representation of the set-up used for experimental work. The pressure of biogas at the outlet of the digester is 2.5 cm of mercury or 1.0466 bar (gauge). The pressure of biogas can be increased using a compressor.

As shown in Fig. 1, raw biogas from the digester is first compressed by using a compressor. The compressed biogas passes through a U-tube manometer, where the gauge pressure is measured in terms of mm of the mercury column. The gas is further passed through a rotameter where the volume flow rate is measured in L per minute (LPM). For removal of hydrogen sulfide, raw biogas is passed through single or multiple packed columns containing various chemical reagents. The contents of purified biogas are monitored using a biogas analyzer. The purified biogas is filled in sampling bags for laboratory analysis. Laboratory analysis of biogas is performed by using gas chromatography in "Nikhil analytical and research laboratory", Sangli, Maharashtra, India. The laboratory is an ISO certified laboratory and approved by the government of India as well as the state government of Maharashtra. The packed column reactors have capacity 1.2 L, out of which aqueous solutions are filled up to 1 L capacity. The aqueous solutions used in the experimental investigations include sodium hydroxide (1.5 Molar), MEA (10% by volume) and calcium hydroxide (1 Molar). The concentrations of MEA, NaOH, and $Ca(OH)_2$ were selected based on their solubility in water, cost of the chemical and references from the literature. Sodium hydroxide and MEA are commercial grade chemicals while calcium hydroxide solution is prepared by dissolving commercially available limestone in water. The solid adsorbents for biogas desulfurization include commercial grade granular activated carbon and steel wool (iron sponge) in the form of scrap chips from the lathe machine. The mass of solid adsorbents filled in the purification column is 500 g. All the aqueous solutions and adsorbents have been selected to minimize the cost of biogas purification. MEA solution after saturation can be regenerated by heating at 120°C while the steel wool adsorbent can be regenerated by simply exposing to atmospheric oxygen. The efficiency of hydrogen sulfide removal and the chemical cost for biogas purification per m^3 of raw biogas are calculated. The variants of experimental investigations include determination of saturation/regeneration time for each of the reagents, calculation of hydrogen sulfide removal efficiency using a single column for each reagent, using multiple purification columns, variations in biogas flow rate and pressure. A detailed description of different experimental investigations is given in the following text.

Determination of the frequency of regeneration for each of the reagents

A chemical reagent reacts with carbon dioxide and hydrogen sulfide in biogas and forms reaction products. The reagent is thus consumed by the contaminant gases and saturates after a definite time. When the reagent in the purification column gets saturated, reduction in hydrogen sulfide content is not observed at the outlet of purification column. The determination of frequency of regeneration (or replacement) for a reagent helps to calculate the

volume of biogas purified by unit quantity of the reagent, size of the scrubbing unit and the chemical cost for biogas purification per unit volume of raw biogas. The cost of chemical required for purification of unit volume (1 m^3) of biogas is calculated. For this purpose, the cost of chemical consumed is divided by the total volume of gas purified by the reagent before saturation. The cost of chemical consumption has a major impact on the total cost of biogas purification. The other factors which contribute to the total cost of purification include capital investment and running cost for energy consumption. The latter factors depend upon the size of purification unit. Hence the chemical cost for purifying unit volume (1 m^3) of biogas has been presented in Table 1. In this study, the contents of raw biogas are initially measured. The raw biogas is passed through the packed column reactor containing a known mass/concentration of the purifying reagent at a flow rate 1 L per min (LPM). The flow rate of raw biogas has been maintained at 1 LPM to ensure sufficient reaction between the contaminants and the reagent. The pressure of biogas at the inlet of purifying column is equal to pressure of biogas at the digester outlet, which is 2.5 cm of mercury or 1.0466 bar (gauge). The details of the frequency of regeneration, the volume of biogas purified and the chemical cost for purification are represented in Table 1.

Biogas purification using single purification columns

In this experiment, hydrogen sulfide removal from biogas is achieved by using a dedicated column for each of the reagent. Raw biogas is made to flow through a single purification column at a flow rate of 2 LPM and a pressure 2.5 cm of mercury. The packed column reactors are filled with either 1 L aqueous solution or 500 g of the solid adsorbent. The composition of raw biogas and purified biogas samples is measured by using gas chromatography. The contents of purified biogas are noted and calculations are made for methane rise (%), carbon

Table 1: Details of the frequency of regeneration and related data for different reagents

Sr. No.	Name of the reagent	Chemical formula	Cost of the reagent $US	Concentration of aqueous solution or mass of the adsorbent	Volume of biogas purified before saturation	Cost of chemical for purification in $US/ m^3
1	Monoethanolamine (MEA^)	C_2H_7NO	6.82 per L	10% by volume	165	Regeneration by heating
2	Sodium Hydroxide (NaOH*)	NaOH	1.36 per kg	1.5 Molar	178	0.46
3	Calcium Hydroxide#	$Ca(OH)_2$	0.2 per kg (lime stone)	1 Molar	117	0.13
4	Granular activated carbon†	C	5.46 per kg	100 g	207	2.64
5	Steel wool† (Iron oxide)	Fe_2O_3	0.2 per kg	500 g	Regeneration up to 5 times	Regeneration by oxidization

Concentration of reagents ^: 10% by volume, *: 1.5 Molar, #: 1 Molar, †: mass 500 g

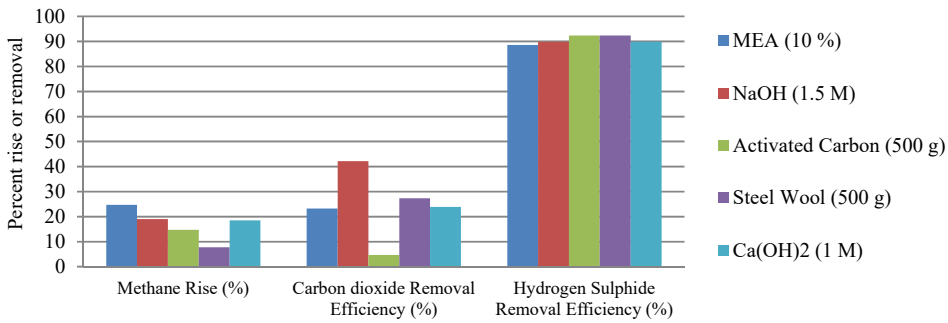


Fig. 2: Efficiency for methane rise or carbon dioxide/hydrogen sulfide removal for purified biogas

dioxide removal efficiency (%) and hydrogen sulfide removal efficiency (%), with reference to the corresponding content in raw biogas. The results for measurement of biogas contents using gas chromatography are given in Table 2. The efficiency calculations for each column of the reagent are represented graphically in Fig. 2.

Biogas purification using multiple purification columns and variation of biogas flow rates

In this experimental study raw biogas is passed through multiple purification columns. Each of the purification columns contains a different reagent. Biogas flow rates are varied as 2 LPM, 5 LPM and 10 LPM, at a constant pressure of 2.5 cm of mercury or 1.0466 bar (gauge). The efficiencies of hydrogen sulfide removal have been calculated for three combinations of reagents, namely activated carbon and steel wool; sodium hydroxide, activated carbon and steel wool; and calcium hydroxide and steel wool. The results of biogas contents measurement using gas chromatography are mentioned in Table 3. The efficiency calculations for methane rise (%), hydrogen sulfide and carbon dioxide removal

Table 2: Contents of raw biogas and purified biogas using single purification columns

Sr. No.	Parameter	Unit	Raw biogas contents	Chemicals Used for Purification				
				MEA^	NaOH*	Activated Carbon†	Steel wool†	$Ca(OH)_2$#
1	Methane	%	56.85	70.89	67.68	65.25	61.27	67.37
2	Carbon dioxide	%	24.41	18.72	14.11	23.26	17.74	18.58
3	Moisture	%	4.48	6.42	7.83	4.93	4.45	5.31
4	Hydrogen sulfide	ppm	790	90	80	60	60	80
		%	0.079	0.009	0.008	0.006	0.006	0.008
5	Other gases	%	14.18	3.96	10.37	6.55	16.53	8.73

Concentration of reagents ^: 10% by volume, *: 1.5 Molar, #: 1 Molar, †: mass 500 g

Table 3: Contents of raw and purified biogas using multiple purification columns and variation in biogas flow rates

Sr. No.	Parameter	Unit	Raw biogas contents	Activated carbon† + steel wool†			NaOH*+ activated carbon†+ steel wool†			Calcium hydroxide# + steel wool†		
				Q_1	Q_2	Q_3	Q_1	Q_2	Q_3	Q_1	Q_2	Q_3
1	Methane	%	56.85	63.56	67.85	67.04	61.36	69.04	63.81	60.31	65.14	70.23
2	Carbon dioxide	%	24.41	19.13	17.20	16.34	22.75	12.32	10.94	15.62	14.06	18.94
3	Moisture	%	4.48	5.49	1.50	1.61	5.04	6.91	7.63	4.75	3.37	1.26
4	Hydrogen Sulfide	ppm	790	40	30	35	30	40	25	40	35	25
		%	0.079	0.004	0.003	0.003 5	0.003	0.004	0.0025	0.004	0.0035	0.0025
5	Other gases	%	14.18	11.82	13.45	15.01	10.85	11.73	17.62	19.32	17.43	9.57

Flow rate of raw biogas Q_1: 2 LPM, Q_2: 5 LPM, Q_3: 10 LPM. Concentration of reagents *: 1.5 Molar, #: 1 Molar, †: mass 500 g

Table 4: Contents of raw and purified biogas using multiple purification columns and variation in biogas pressure

Sr. No.	Parameter	Unit	Raw biogas contents	Activated carbon† + steel wool†			NaOH* + activated carbon† + steel wool†			Calcium hydroxide# + steel wool†		
				P_1	P_2	P_3	P_1	P_2	P_3	P_1	P_2	P_3
1	Methane	%	56.85	63.56	67.76	60.33	61.36	74.14	63.23	60.31	63.57	72.53
2	Carbon dioxide	%	24.41	19.13	24.16	19.52	22.75	14.45	20.88	15.62	18.29	13.73
3	Moisture	%	4.48	5.49	3.64	1.30	5.04	2.70	2.53	4.75	3.12	2.42
4	Hydrogen sulfide	ppm	790	40	25	25	30	35	40	40	30	25
		%	0.079	0.004	0.0025	0.0025	0.003	0.0035	0.004	0.004	0.003	0.0025
5	Other gases	%	14.18	11.82	4.44	18.85	10.85	8.71	13.36	19.32	15.02	11.32

Gauge pressure of raw biogas P_1: 2.5 cm of Hg, P_2: 5 cm of Hg, P_3: 7.5 cm of Hg.
Concentration of reagents *: 1.5 Molar, #: 1 Molar, †: mass 500 g.

efficiency (%) for each combination of the reagents are represented graphically in Fig. 3.

Biogas purification using multiple purification columns and variation of biogas pressure

In this experimental study raw biogas is passed through multiple purification columns. Each of the purification columns contains a different reagent. Biogas pressures are varied as 2.5 cm of mercury or 1.0466 bar (gauge), 5 cm of mercury or 2.0932 bar (gauge) and 7.5 cm of mercury or 3.1398 bar (gauge) by throttling the compressor outlet valve. The efficiencies of hydrogen sulfide removal have been calculated for three combinations of reagents, namely activated carbon and steel wool; sodium hydroxide, activated carbon and steel wool; and calcium hydroxide and steel wool. The results of biogas contents measurement using gas chromatography are mentioned in Table 4. The efficiency calculations for methane rise (%), hydrogen sulfide and carbon dioxide removal efficiency (%) for each combination of the reagents are represented graphically in Fig. 4.

RESULTS AND DISCUSSIONS

Frequency of regeneration for the reagents

The results for the frequency of regeneration and the cost of chemical for purifying unit volume of biogas are represented in Table 1. It is seen that out of the solid desulfurizing substances, steel wool is a better option due to low-cost and the ability for regeneration. Out of the aqueous solutions, calcium

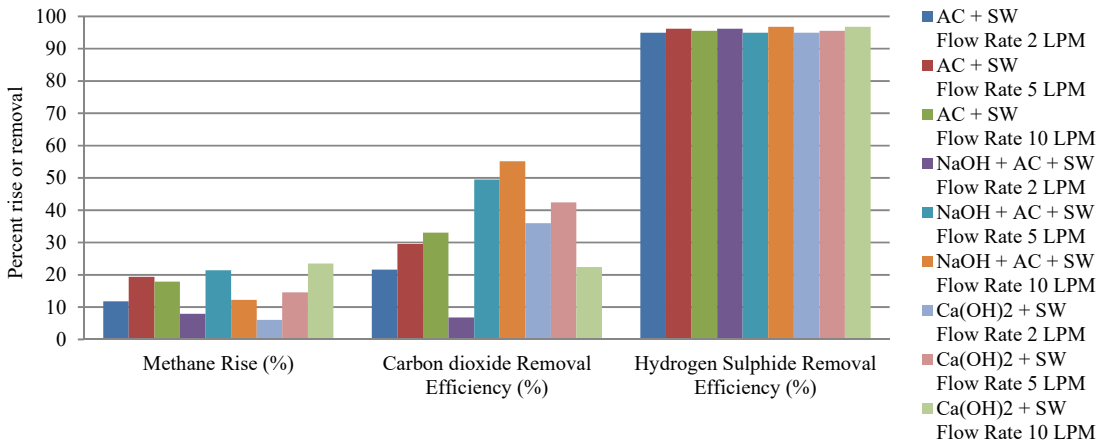


Fig. 4: Biogas purification efficiencies using multiple purification columns at different biogas pressures

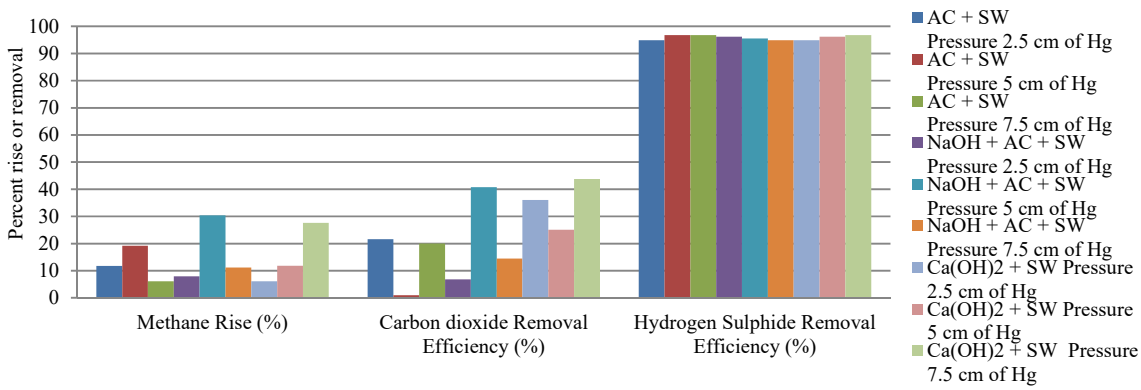


Fig. 3: Biogas purification efficiencies using multiple purification columns at different biogas flow rates

hydroxide is preferable due to lower cost of chemical and the ease of availability.

Biogas purification using single purification columns

Results for measurement of biogas contents using gas chromatography are represented in Table 2.

From Table 2 it is seen that all the reagents can reduce hydrogen sulfide in biogas up to or below 90 ppm. The reagents activated carbon and steel wool are more effective for hydrogen sulfide removal from biogas and give minimum hydrogen sulfide content of 60 ppm in purified biogas. Calculations of various efficiencies such as methane rise, efficiencies for H_2S and CO_2 removal using single purification columns are represented in Fig. 2.

From Fig. 2, it is observed that hydrogen sulfide removal efficiencies for the reagents MEA, sodium hydroxide and calcium hydroxide using single purification columns are slightly lower (between 88.61% and 89.87%). This is due to the fact that these chemicals are also effective for removal of carbon dioxide from biogas and increasing the heating value. The chemicals calcium hydroxide and sodium hydroxide are cost effective and easily available than MEA. The reagents MEA, sodium hydroxide and calcium hydroxide can be preferable in the applications where improvement in heating value of biogas is also desired, for example running of

Table 5: Comparison of results and details of experimental work for the present and previous works

Results obtained	Details of experimental work	References
▪ Hydrogen sulfide (H_2S) removal efficiency more than 95% ▪ Regenerated steel wool is as good as new steel wool for H_2S removal	▪ Steel wool used for H_2S removal from biogas ▪ Three polyvinyl columns containing steel wool arranged in series	Magomnang and Villanueva, 2015
▪ H_2S concentration could reach below 50 ppm, which is acceptable for running internal combustion engines ▪ Maximum H_2S removal efficiency is 95%	▪ Use of zero-valent iron for H_2S removal from biogas ▪ H_2S concentration in raw biogas between 138-211 ppm	Rashed and Torii, 2015
▪ Purified biogas: CO_2 between below detectable level up to 1.47%. H_2S between 8-12 ppm ▪ H_2S removal efficiency between 55.55% and 70.37% ▪ Water scrubber efficiency: 30%	▪ Iron oxide for H_2S removal ▪ CO_2 in feed biogas: 4.55 to 5.28%, H_2S in feed biogas 27 ppm ▪ Regeneration of sodium carbonate using algal culture ▪ Another run using water scrubbing	Mohanakrishnan and Joseph, 2016
▪ Purified biogas from first run: 102 ppm H_2S or 89.65% H_2S removal efficiency ▪ Purified biogas from second run: H_2S 87 ppm or 91.18% H_2S removal efficiency	▪ Raw biogas: methane 61.22%, CO_2 32.01%, H_2S 986 ppm ▪ Iron oxide for H_2S removal ▪ First run using dry lime and potassium hydroxide for CO_2 removal ▪ Second run using sodium hydroxide and calcium hydroxide for CO_2 removal	Shah *et al.*, 2016
▪ H_2S removal efficiency between 85% and 96%	▪ Chemicals iron oxide, zero-valent iron, and iron chloride for H_2S removal ▪ Calcium oxide for CO_2 removal	Rashed and Torii, 2017
▪ H_2S removal efficiency between 88.61% to 92.41% using single purification columns ▪ H_2S removal efficiency between 94.94% to 96.84% using multiple purification columns ▪ Biogas flow variations and pressure variations have a less significant effect on H_2S removal efficiency and more significant effect on CO_2 removal efficiency	▪ Raw biogas H_2S content: 790 ppm ▪ Chemical absorption technique for H_2S removal using packed columns ▪ Reagents for H_2S removal (low-cost, commercial grade): sodium hydroxide, calcium hydroxide, monoethanolamine (MEA), activated carbon and steel wool (iron oxide) ▪ Effect of single/multiple purification columns, biogas flow and pressure variations on H_2S removal efficiency ▪ Biogas generated from floral waste feedstock	Present work

stationery engines to generate electricity. Hydrogen sulfide removal efficiency using single purification columns is higher (92.41%) for the reagents activated carbon and steel wool. The cost considerations and regeneration aspect suggest that steel wool is a preferred choice for desulfurization of biogas. These reagents are desirable when hydrogen sulfide removal from biogas is the priority, for minimizing corrosion and health hazards. From Figs. 2, 3 and 4, it is observed that use of single purification column for hydrogen sulfide removal gives lower efficiency as compared to the use of multiple purification columns. Use of single reagent column(s) for biogas purification is more affordable and feasible from practical application point of view.

Biogas purification using multiple purification columns and variations of biogas flow and pressure

Table 3 shows the effect of biogas flow rate variations on the contents of purified gas using different combinations of reagents.

The combination of activated carbon and steel wool gives minimum hydrogen sulfide content when biogas flow rate is maintained at 5 LPM. The other two combinations of reagents mentioned in Table 2 give minimum hydrogen sulfide content when biogas flow rate is maintained at 10 LPM. Table 4 shows the effect of biogas pressure variations on the contents of purified gas using different combinations of reagents.

The combination of activated carbon and steel wool, and also the combination of calcium hydroxide and steel wool gives minimum hydrogen sulfide content of 25 ppm. The remaining combination of sodium hydroxide, activated carbon gives minimum hydrogen sulfide content of 30 ppm. This combination will also need higher cost of purification per liter of biogas and thus presents a less viability for practical applications. The results for biogas purification using multiple purification columns and variations in biogas flow rates are represented in Fig. 3 and the results of biogas purification using multiple purification columns and variations in biogas pressure are represented in Fig. 4. It is observed that the use of multiple purification columns gives higher efficiencies of H_2S removal with an obvious increase in the cost of chemicals. All the combinations of purification columns subjected to the variations of biogas flow rate and pressure give H_2S removal efficiencies between 94.94% and 96.84%. The combination of reagents steel wool and activated carbon gives the highest H_2S removal efficiency at biogas flow rate of 5 LPM and pressure 5 cm of mercury (gauge). The second combination of sodium hydroxide, activated carbon and steel wool gives the highest H_2S removal efficiency at biogas flow rate of 10 LPM and pressure 2.5 cm of mercury (gauge). The combination of calcium hydroxide and steel wool gives the highest H_2S removal efficiency at biogas flow rate of 10 LPM and pressure 7.5 cm of mercury (gauge). The purification columns comprising a combination of sodium hydroxide, activated carbon and steel wool gives the highest efficiencies for H_2S removal and methane enrichment. But the operational cost is also high for this combination. The purification columns comprising a combination of calcium hydroxide and steel wool gives the minimum operating cost with satisfactory H_2S removal efficiency and methane enrichment. The feasibility of operation using multiple purification columns with given combinations of reagents need to be verified during large scale operations.

The variations of biogas flow rate and biogas pressure have a less prominent effect on H_2S removal efficiencies. The hydrogen sulfide removal efficiencies for all the experimental studies are obtained between 94.94% and 96.84%. But, the variations of biogas flow rates and biogas pressure have a considerable effect on carbon dioxide removal efficiency. Dry desulfurization using steel wool presents the most appropriate option for hydrogen sulfide removal from biogas, in the context of cost considerations and the feasibility for use by common end users. Additional use of calcium hydroxide or sodium hydroxide columns is recommended for improved carbon dioxide removal at the lower operational costs. A comparison of experimental results for the present work and previous works by other researchers is presented in Table 5. It can be seen that the hydrogen sulfide removal efficiencies obtained in the present work are comparable to those obtained in the previous works.

CONCLUSIONS AND FUTURE WORK

Removal of hydrogen sulfide from biogas is a necessary step for minimizing the corrosion of metallic components and health hazards. Most of the common end-users use biogas for cooking applications and seldom use biogas desulfurization techniques. Thus there is a great need to disseminate

low-cost and easy-to-use biogas desulfurization techniques amongst these users. The chemical absorption technique is a viable option for hydrogen sulfide removal from biogas due to operation at near ambient pressure and temperature conditions and smaller energy requirements. The present experimental work is an attempt to propagate cost-effective and user-friendly chemical absorption technique using low-cost commercial grade chemicals. In the present experimental work, high H_2S removal efficiencies (88.61% to 92.41%) were obtained using single purification columns, suitable for applications in domestic biogas plants. Still higher H_2S removal efficiencies (94.94% to 96.84%) were obtained using multiple purification columns. Variations in biogas flow rate and pressure have a comparatively less influence on hydrogen sulfide removal efficiencies whereas carbon dioxide removal efficiency is significantly affected by these variations. The feasibility for implementation on a large-scale for the present combinations of chemicals needs to be verified. Further work can deal with the use of purification columns on the suction side of the compressor to minimize the corrosion of compressor moving parts and storage tank. Future work can also focus on minimizing the energy requirements for regeneration of chemicals.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

ABBREVIATIONS

AC	Activated carbon
$CaCO_3$	Calcium carbonate
$Ca(OH)_2$	Calcium hydroxide
CH_4	Methane
CO_2	Carbon dioxide
$FeCl_3$	Iron chloride
Fe_2O_3	Iron oxide
g	gram(s)
h	Hour
Hg	Mercury
H_2S	Hydrogen sulfide
ISO	Internal organization for standardization
kg	kilogram(s)
L	Liter
LPG	Liquefied petroleum gas
LPM	Litre(s) per minute
MEA	Monoethanolamine
m^3	Cubic meter(s)
Na_2CO_3	Sodium carbonate
$NaHCO_3$	Sodium bicarbonate
NaOH	Sodium hydroxide
Ppm	Parts per million
^oC	Degree Centigrade
%	Percent
SW	Steel wool
$US	US dollar

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