BIOGAS PRODUCTION BY CO-DIGESTION OF APPLE POMACE AND PINE NEEDLES

M. Sc. Thesis

Submitted

by

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SUPERVISOR'S CERTIFICATE

This is to certify that the work reported in the M.Sc. dissertation entitled "BIOGAS PRODUCTION FROM CO-DIGESTION OF APPLE POMACE AND PINE NEEDLES" submitted by Smriti Gaba (207825) at Jaypee University of Information Technology, Waknaghat, Solan, Himachal Pradesh, India, is bonafide record of her original work. It has not been submitted elsewhere for any other degree or diploma.

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DECLARATION

I hereby declare that the work reported in the M.Sc. dissertation entitled "BIOGAS PRODUCTION FROM CO-DIGESTION OF APPLE POMACE AND PINE NEEDLES" submitted at Jaypee University of Information Technology, Waknaghat, Solan, Himachal Pradesh, India, is an authentic record of my work carried out under the supervision of Dr. Sudhir Kumar, Dept. of Biotechnology and Bioinformatics and Dr. Ashish Kumar, Dept. of Civil Engineering at Jaypee University of Information Technology, Waknaghat, Solan, Himachal Pradesh-173234, India. I have not submitted this work elsewhere for any other degree or diploma.

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Abstract

Apple pomace and pine needles are food and agricultural wastes, respectively, that causes disposal problems. As a solution, both of the substrates can be converted to a useful energy source i.e. biogas, through the process of anaerobic digestion. This study describes the suitability of apple pomace and pine needles as substrates for biogas production. Four digesters each of 40 litre named as digester 1 (D1), digester 2 (D2), digester 3 (D3) and digester 4 (D4) were fed with apple pomace, pine needles, 90% apple pomace with 10% pine needles and 75% apple pomace with 25% pine needles, respectively. The batch digesters were operated at ambient mesophilic conditions, they were fed at a period of every five days with 0.04 g VS/L/day as organic loading rate (OLR). The total solids, volatile solids and daily pH and temperature variations were observed. During the period of 28 days, 6.97 L, 15.86 L, 25.38 L and 9.67 L of biogas was produced in D1, D2, D3 and D4, respectively. The highest methane content was 84.4% obtained from pine needles.

List of abbreviations

AD - Anaerobic digestion

BOD – biological oxygen demand

COD – chemical oxygen demand

C/N – carbon to nitrogen ratio

CH_4 – methane

CO_2 – carbon dioxide

LPG – liquid petroleum gas

CNG – compressed natural gas

OLR – organic loading rate

FOM – first order kinetic model

H_2S – hydrogen sulphide

O_2 – oxygen

GHG – greenhouse gases

DO – dissolved oxygen

FAS – ferrous ammonium sulphate

TWh – Terawatt-hour

N – Normality

VFA – Volatile fatty acids

List of symbols

k – hydrolysis rate

P_O – cumulative methane production

P – maximum biogas yield

T – time

T_S – total solids

F_S – fixed solids

V_S – volatile solids

W_{105} – weight at 105^0C

W_{600} – weight at 600^0C

W_{C1} – weight of crucible

Chapter 1

Introduction

1.1) Major issues globally

Major challenge faced globally is the depletion of non-renewable energy resources and if exploited with the same pace, we will soon run out of reserves. According to a research, we shall run out of oil by next 51 years, coal in 114 years and natural gas in 53 years [1] as shown in figure 1.1 where y-axis and x-axis represents energy resource and time in years, respectively.

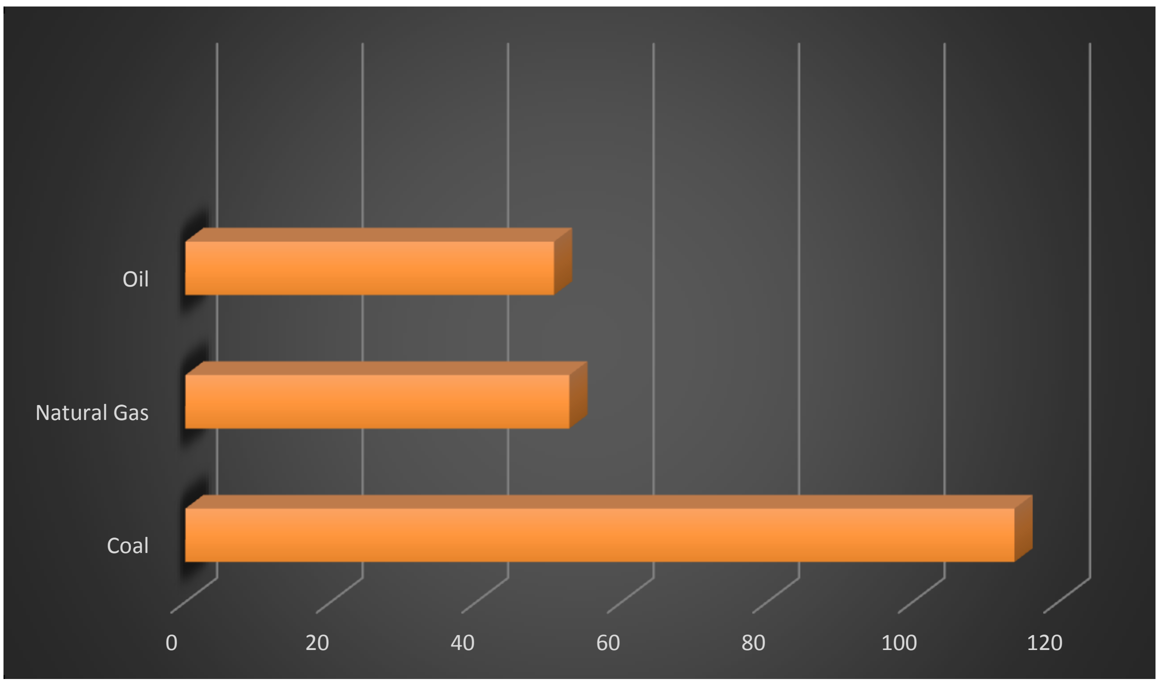

Fig 1.1) Status of fossil fuels [1].

We are hugely dependent on fossil fuels and wondering over the fact that they are irreplaceable. Fossil fuels usage has been rising tremendously since their discovery in 1850's. Consumption of coal, oil, gas were nearly 40,000 TWh, 100,000 TWh and more than 120,000 TWh respectively in the year 2019 [2] and has been rising continuously.

Non-renewable energy consumption hugely dominates renewable energy consumption. Renewables meet only 5% of energy needs whereas non-renewables including oil, natural gas, coal contributes 33%, 24%, 27% respectively [3] as shown in figure 1.2. Fossil fuels accounts for

84% of world's total energy consumption in 2019. To avoid the future energy crises researches have been working globally to go green and renewables contribution is increasing.

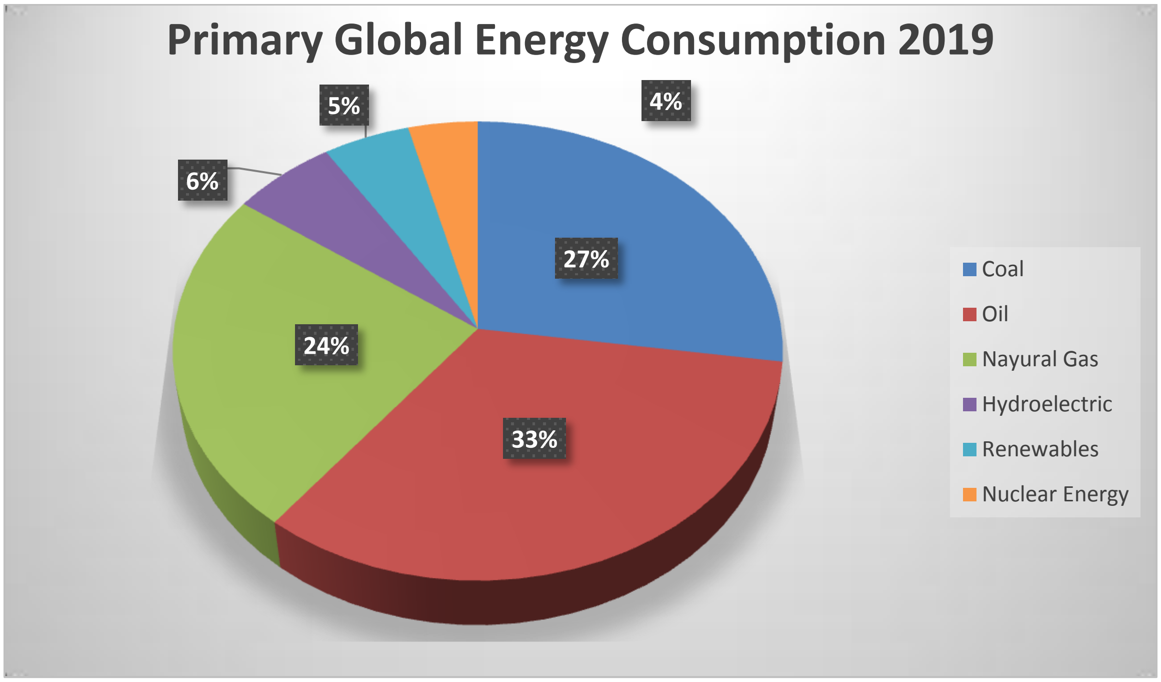

Fig 1.2) Global energy consumption [3].

The second major challenge faced today is waste management. In the year 1900, 300,000 tones of waste per day was produced which due to increasing urbanization increased to 3 million tones waste production per day, this is estimated to become twice by 2025 [5].

1.2) Step towards solution

The only solution to the prevailing situation is shifting the dependence from non-renewable energy resources and switching to renewable energy sources that include solar energy, wind energy, geothermal, hydropower and biofuels. Recently, the focus of energy sectors is towards biofuels due to sustainability and energy security [4]. Major biofuels include bioethanol, biohydrogen, biogas which are prepared from biomass and they are environmental friendly. Biomass includes kitchen waste, agricultural waste and organic industrial waste.

Biogas being a clean and environmental friendly energy source has been gaining attention. It has been used in cooking and lighting purposes and no wonder it could become future fuel resource. Biogas majorly constitutes methane (60-80%) and carbon dioxide (20-30%). The percentage of these gases depends on the substrate used. Since CO_2 is neither flammable and nor does it support combustion, therefore it's percentage has to be minimized in order to utilize biogas. The goal is to find out the substrates with high methane yield and minimum carbon dioxide (<20%). Recent study focuses on production of biogas by co-digestion of apple pomace and pine needles and to access the gas composition of biogas obtained from apple pomace and needles independently and during co-digestion. The goal of the study is to promote waste utilization and production of good quality energy resource.

Objectives of study-

The study has following objectives-

- Optimization of biogas production through co-digestion of apple pomace and pine needles.
- Techno-economic analysis of biogas production from co-digestion of apple pomace and pine needles.

Chapter 2

Literature review

2.1) Biogas:

Biogas, a gaseous fuel, is a mixture of gases primarily containing methane (nearly 60%) and carbon dioxide (35%) which is formed by microbial anaerobic digestion of organic matter. It also contains traces of ammonia, oxygen, moisture, nitrogen, hydrogen etc.

Decomposition of organic matter occurs in the absence of oxygen by anaerobic bacteria. The content of organic matter in the substrate/waste is reduced through biological conversion of organic carbon to biogas during anaerobic digestion [6]. Substrates used for biogas production can be kitchen waste, animal dung (cow, pig, sheep etc.) and agricultural waste. The methane percentage of biogas depends on the substrate used and the calorific value of biogas depends on methane percentage. Biogas with methane content of 50% (minimum) and 80-84% (maximum) has calorific value of 4281 and 6849 kcal/m^3 respectively [7]. Biogas is used for cooking and lighting purposes, as it is produced from waste therefore it helps in soil and water pollution reduction, also the leftover after gas production is used as fertilizer as shown in figure 2.1.

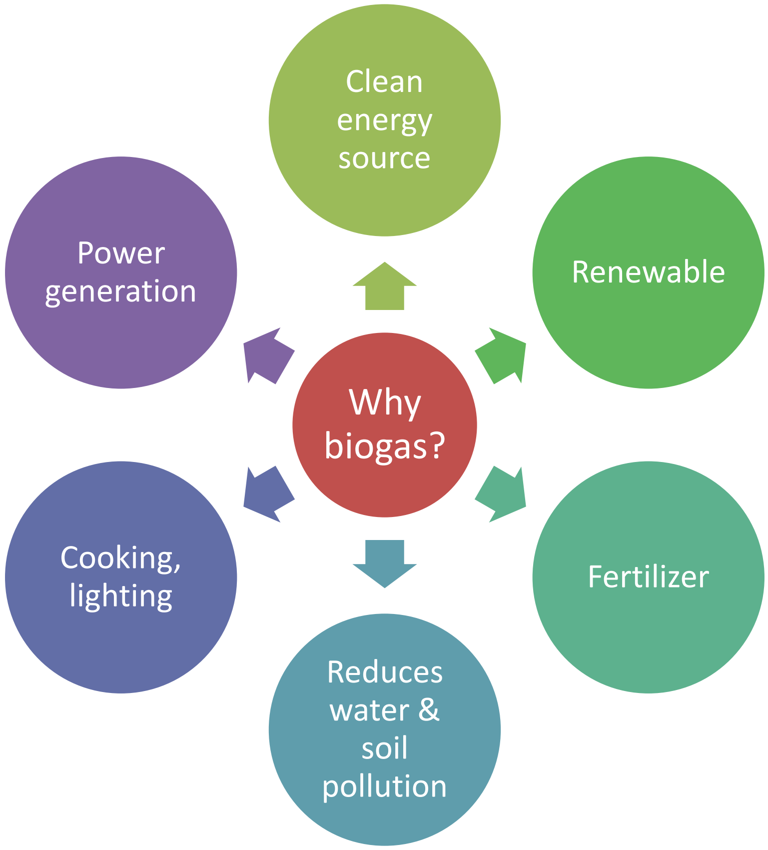

Fig 2.1) Uses of biogas.

At an average biogas has calorific value 5137 Kcal/U.M. which is higher than dry wood (1800-2200 Kcal/U.M.) and lignite (1800-3800 Kcal/U.M.) [8], it signifies that biogas is valuable and can be used for cooking and lighting purposes. In addition to methane percentage, C/N ratio is also major criteria determining suitability of substrate used, it is important factor formulating fermentation media for biogas production. Optimal C/N ratio is 15-25 in single stage anaerobic digestion while it is 10-45 (step 1) and 20-30 (step 2) in two stage digestion [9]. The amount of methane percent given by different substrates having different C/N ratios is shown in table 2.1.

Substrate	C/N ratio	Methane%	Reference
Wheat straw	87/128	78.5	[8],[10]
Rice straw	67	-	[8]
Corn cobs	56	-	[8], [9]

Barley straw	56	-	[8], [10]
Lucerne	18	77.7	[8], [10]
Potato stalks	22	-	[8]
Tree leaves	41	-	[8]
Soy & bean stalks	32	-	[8]
Horse dung	24	66	[8], [10]
Sheep dung	29	65	[8], [10]
Cow dung	25	61.4/64.9	[8]
Pig manure	13	61.2/63.4/64.6	[8], [10]
Night soil	29	-	[11]–[14]
Chicken waste	15	59.7/64.6	[8]
Kitchen waste	-	62.5	[15]
Water hyacinth	-	67.5	[15]
Cattle waste	25	50-60	[10]
Pig+cow mix	-	65	-
Poultry droppings	7.3	68	[10]
Blood	3	-	[11]–[14]
Urine	0.8	-	[11]–[14]
House waste	2	-	[11]–[14]
Corn silage	-	52	[10]
Bean stalk	32	-	[11]–[14]
Rooted sawdust	200-500	-	[11]–[14]
Peanut stalk & leaves	19	-	[11]–[14]
Amaranthus	11	-	[11]–[14]
Purslane	8	-	[11]–[14]
Cockshoot	19	-	[11]–[14]
Raw garbage	25	-	[11]–[14]
Seaweed	79	-	[11]–[14]
Bread	25	-	[11]–[14]

Potato tops	26	-	[11]–[14]
Cabbage	12	-	[11]–[14]
Tomato	128	-	[11]–[14]
Dried leaves	-	58	[10]
Beet leaves	-	84.8	[10]
Grass	-	84	[6]
Maize sillage	-	50-55	[6]
Rye silage	-	55	[6]
Vegetable waste	-	60	[6]
Sugar beet stains	-	54-55	[6]
Sugar beet	-	53-54	[6]
Various herbs	25	-	[15]

Table 2.1) Comparison of substrates used for production of biogas with C/N ratio and methane yield.

2.2) Comparison of Biogas, Liquified petroleum gas and Compressed natural gas

Major problem with biogas not being used as fuel is the presence of CO_2. If CO_2 is separated from biogas, it can be used to run vehicles as CNG. Biogas fuelled vehicles can reduce CO_2 emissions by 75%-200% in comparison to fossil fuels [16].

Biogas has potential to be used as cooking fuel in case of LPG crises. 600kg/day kitchen waste collected can produce 32kg/day of biogas which is equal to 2 LPG cylinders per day [17]. Comparison of biogas, LPG and CNG is shown in table 2.2.

Characteristics	Biogas	LPG	CNG
Type of energy	Renewable	Non – renewable	Non – renewable
Composition	CH_4, CO_2	Propane, butane	CH_4
Calorific value (kcal/U.M.)	5137 [8]	22000 [8]	8500 [8]

Table 2.2) Comparison of biogas and major heat resources.

Though LPG and CNG have more calorific value than biogas but the fact that can not be ignored is that biogas is renewable energy resource and environmental friendly.

2.3) Process of anaerobic digestion

Anaerobic digestion is carried out in biogas reactors in presence of microbes. This is four step process that includes hydrolysis, acidogenesis, acetogenesis and methanogenesis. The steps in biogas production, substrate, product and bacteria involved is highlighted in table 2.3.

Process	Substrate	Product	Type of bacteria	Bacteria involved [18]
Hydrolysis	Carbohydrates, proteins, fats	Simple sugars, amino acids, fatty acids	Hydrolytic bacteria	*Bacteriodes, Clostridium, Acetovibrio, Fibrobacter*
Acidogenesis	Simple sugars, amino acids, fatty acids	Volatile fatty acids, alcohol, H_2, CO_2	Fermentative bacteria	*Bacteriodes, Clostridium, Lactobacillus*
Acetogenesis	VFA, H_2, CO_2	Acetic acid(CH_3COOH), H_2, CO_2	Syntrophic bacteria	*S. wolfei, S. bryantii, S. sapovorans*
Methanogenesis	Acetic acid, H_2, CO_2	Methane(CH_4), CO_2, traces of O_2, H_2S	Methanogens/Acetoclastic H_2 oxidizing bacteria	*Methanosaeta sp. Methanobrevibacter, Methanobacterium, Methanospirillum, Methanogenium*

Table 2.3) Steps involved in biogas production

2.3.1) Hydrolysis

Biomass consists of polymers that needs to be broken down to simpler components for conversion into biogas, the breakdown of complex polymers is facilitated by enzymes secreted by hydrolytic bacteria. Hydrolysis rate depends on composition of substrate, temperature, pH, particle size [18]. This process is carried out by hydrolytic bacteria which hydrolyses complex biomolecules i.e. lipids, proteins and sugars.

2.3.2) Acidogenesis

Sugar monomers are converted to pyruvate, fermentative bacteria converts amino acids and pyruvate to organic acids (acetate, butyrate), CO_2, H_2, alcohol. This process occurs in presence of acidogenic bacteria. It is called acid-forming stage due to formation of acids. The bacteria performing at this stage strive at acidic pH of 5.5-6.5.

2.3.3) Acetogenesis

This stage is marked by the formation of acetic acid and takes place by assistance of acetogenic bacteria. Acetogenic bacteria are responsible for acetate production but hydrogen may inhibit acetogenic bacteria therefore hydrogenotropic bacteria divert hydrogen and combine it with CO_2 to produce biogas, hence, acetogenic bacteria and hydrogenotrophic bacteria live in syntrophic relationship to prevent the inhibitory effect caused by H_2 [19].

2.3.4) Methanogenesis

Methanogens are archaebacteria found at rate of 10^8 per milliliter in anaerobic digesters [19]. Methanogens are categorized as acetoclastic methanogens which form methane by using acetic acid and hydrogenotrophic methanogens that form methane from H_2 and CO_2. The amount of methane in biogas depends on several factors like the substrate used, C/N ratio, temperature etc.

2.4) Major factors affecting anaerobic digestion

There are several factors that affects biogas production, the major factors are listed in figure 2.2.

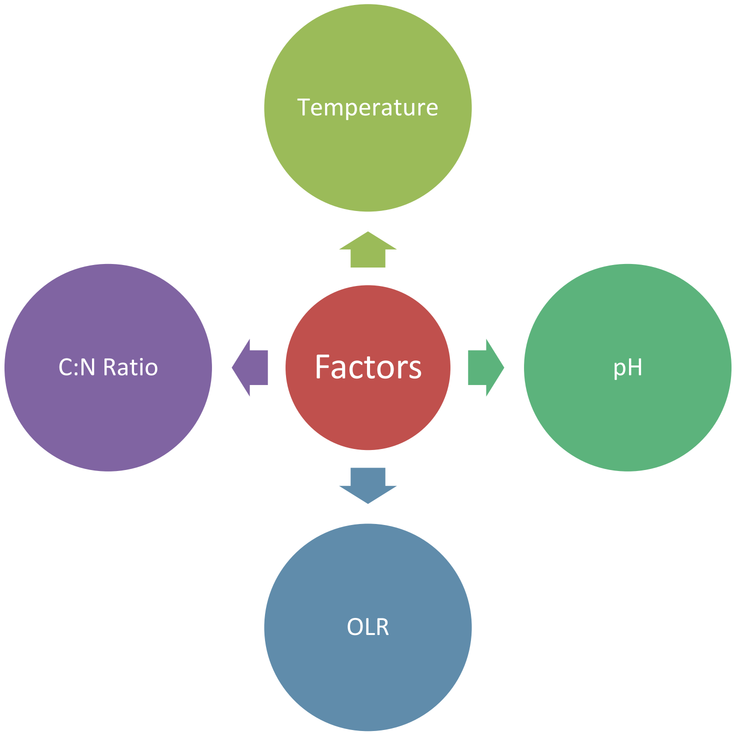

Fig 2.2) Major factors affecting biogas production.

2.4.1) Temperature

Bacteria show high activity at optimum temperature. On the basis of temperature anaerobic microbes are categorized as- a) Psychrophiles- They are active at 12^0C-24^0C. b) Mesophiles- They are active at 22^0C-40^0C. c) Thermophiles- They are active at 50^0C-60^0C. [20].

Temperature effects metabolism of microbes therefore biogas yield is more at mesophilic to thermophilic range because of increased reaction rate and increased solubility of substrate. However, thermophilic system requires more energy and may increase cost. High methane percentage is achieved at 35-37^0C (mesophilic) and 55^0C (thermophilic) [21]. Methane generation rate increases with increase in temperature. Methane generation rate for crop residues has reported to be 108mL/L/day, 310mL/L/day and 366mL/L/day at 18^0C, 25^0C and 37^0C [22]. Kim et. al. found variable methane percentage at different temperature, 59% and 57% methane was achieved at 55^0C and 35^0C [23] whereas in another similar experiment 65%, 62% and 58% was obtained at 35^0C, 55^0C and 20^0C [24].

2.4.2) pH-

The pH of anaerobic digesters effects the activity of anaerobic microbes. The pH range near neutral i.e. 6.3-7.8 is optimum for anaerobic microbes [25]. The hydrolytic stage has pH of 5.5-7 whereas pH is 6.5-8 during methanogenesis [26-29]. The digester can become more basic (pH>7.8) or more acidic (pH<5.5) due to accumulation of ammonia and volatile fatty acids, respectively. Buffer is added to balance more acidity or more basicity, e.g. lime is added in case system becomes acidic as low pH is inhibitory to anaerobic digestion. The pH of biomass determines biogas production, addition of acidic substrate like food alone may not give biogas. pH of 6.5-8.2 is also reliable for anaerobic digestion process [30].

2.4.3) Organic loading rate-

OLR is the amount of substrate fed to the reactor per unit volume. OLR is an important factor as high OLR may lead to volatile fatty acids accumulation while low OLR may not generate enough biogas. Psychrophilic system and mesophilic system requires low OLR, also in winters low OLR is considered while high OLR (up to 7g VS/L/day) is considered during summers [31-33]. Jewell et. al. (2006) produced biogas using apple pomace with OLR as 5g/L/day [34]. Tripathi et al. (2015) produced biogas from pine needles with OLR as 0.09g VS/L/day [35].

2.4.4) Carbon to Nitrogen ratio-

The feedstock used for biogas production should have optimum ratio between 15-25. Nitrogen is required for growth of micro-organisms in absence of oxygen [36]. C/N ratio value is so because carbon is used by microorganisms 25 times quicker than nitrogen. If nitrogen is higher, C/N ratio will be low and digestion will be inhibited [36-37].

There is different C/N ratio for each substrate, table 1.1 compares C/N ratio of different substrates utilized in biogas generation For optimum C/N ratio, co-digestion of substrates is suggested [38]. Here, we are producing biogas with co-digestion of apple pomace and pine needles for better biogas yield.

2.5) Status of substrates-

2.6.1) Apple pomace- It is the solid residue left after extraction of apple juice from apples which accounts for 25% of total biomass [39]. Worldly apple production is approx 54.2 million around the world as shown in figure 2.4. Apple in apple processing units is used for preparation of juice, cider, jellies etc. which generates apple pomace as leftover. Apple pomace has been used as animal feed, the rest is burnt off giving out GHGs emissions [39]. The quantity of apple produced in different countries is given below in table 2.4. Germany is topmost producer of apple pomace with 250 thousand tones followed by Japan, Iran, United States, Spain, New Zealand, Brazil and India.

Country	Quantity(thousand of tones)	Reference
Germany	250	[40]
Japan	160	[41]
Iran	97	[42]
United States	27	[43]
Spain	20	[44]
New Zealand	20	[45]
Brazil	13.75	[46]
India	3-5	[47]

Table 2.4) Quantity of apple pomace generated.

For waste disposal alleviation, bioethanol [48] and biobutanol [49] have been made from apple pomace. Nutraceuticals, antioxidants and pectin have also been made from apple pomace [49-51]. Apple pomace have also been used to make biogas [34].

India produces more than 20 lakh tones of apples yearly. States wise apple production is shown in table 2.5.

States	Apple production
Jammu & Kashmir	15.4 lakh tones
Himachal Pradesh	3.8 lakh tones
Uttrakhand	50 thousand tones
Arunachal Pradesh	6.4 thousand tones

Table 2.5) Apple production in India, 2020 [52].

2.6.2) Pine needles- Pine trees are found in Northern hemisphere and in few parts in southern hemisphere. These are found in variety of environments, especially adapted to elevation. In India, pine trees are found in Himalayan region. In Himachal Pradesh, 1.25 lakh hectares is covered with pine forests and during month of April and June 1.2 tones of pine needles are shed. Being combustible these needles lead to forest fires destroying wildlife and plantations [53]. Therefore, removal of pine needles is important and as an advantage it can be utilized elsewhere. Pine needles are used in electricity production [54] and in briquette production which is used as source of lighting [55]. They have also been utilized for biogas production [35], [56].

2.6) Characteristics of substrates

- Apple pomace has high moisture content of 70%-80%.
- It has high BOD and COD values.
- It is susceptible to degradation by microbes.
- High carbohydrate content (48-62%) and good protein content (2.94-5.67%) on dry weight basis [57].
- It contains simple sugars, pectin, fibres and minerals
- It also has lipids (2.45%) in form of fibres [57].
- Pine needles have high cellulose content of 61.73%.
- Good calorific value of 19.44 MJ/kg.
- They have good volatile solid to total solid ratio.

2.7) Substrates and co-digestion-

The maximum methane yield from protein, lipid and carbohydrate is 1.0, 0.58, 0.37 m^3 CH_4/ kg organic dry matter, respectively.

Apple pomace contain high carbohydrate content, the above information signifies that high carbohydrate content can’t form biogas. Acidic substrates like food waste, apple pomace leads to formation of volatile fatty acids and inhibition of system. Therefore we hereby prefer adding lignocellulosic waste like pine needle to balance acidity of apple waste. Moreover, co-digestion has certain benefits-

a) Increases nutrient content of waste

b) Provides better digestibility

c) Dilute venomous compounds like fats, ammonia that may slow digestion process

d) Enhances biogas and methane yield [35].

Chapter 3

Material and methods

3.1) Study Location

The experiment was carried out at India's Jaypee University of Information Technology (JUIT) in Himachal Pradesh. Himachal Pradesh is one of India's northern mountainous states, with elevations ranging from 450 metres to 6,826 metres above sea level. JUIT is specifically located in Waknaghat, a tiny village in the area of Solan. Waknaghat sits at a height of 1,544 metres above sea level, with geographical coordinates of 31.0079 degrees north, 77.0881 degrees east.

3.2) Details of Experimental Setup

The floating drum anaerobic reactor was utilized in this experiment. The reactor and the gasholder were the reactor's two major components. The reactor had a volume of 40 litres and the gasholder had a volume of 25 litres. They were all cylinders manufactured of Poly Vinyl Chloride (PVC). We set up 4 digesters of 40 L having gas holding capacity of 25 L. Gas holder has diameter of 0.30m and the diameter of holding cylinder is 25cm. The fitting contain ½ inch tank connection nipple, ½ inch valve and gas cork. The digesters were pre-started by adding slurry from an established food waste anaerobic reactor. Figure 3.1 show the set-up of reactors. The experimental set-up was permitted to operate at a range of temperatures in the environment.

Figure 3.1) Anaerobic digesters used for biogas production.

3.3) Details of Substrate, its Characterization, and Inoculum

In this study, apple pomace and slurry of crushed pine needles was used as a substrate as shown in figure 3.2. To choose the best OLR substrate, a preliminary assessment of the substrate was required. Analytical criteria such as moisture levels, total solids, and volatile solids were used to characterise the substrate. Slurry was used as an inoculum and was taken from JUIT's existing food waste reactor.

Figure 3.2) Apple pomace and dried pine needles

3.4) Nature of substrates

Apple pomace and pine needles have total solids as 17.26% and 19.75% respectively, obtained at 105^0C and volatile solids of 16.86% and 18.07% respectively, obtained at 600^0C. Both the substrates have good volatile solids to total solids ratio, therefore, they are good producers of biogas. The characteristics features of substrates is given in table 3.1.

The total solids, fixed solids and volatile solids has been calculated using formula,

$T_s = W_{105} - W_{C1}/ W_{sample} * 100\%$

$F_S = W_{600} - W_{C1}/ W_{sample} * 100\%$

$V_s = T_S - F_S$

Here, F_S – fixed solids, V_S – volatile solids, T_S – total solids, W_{105} – weight at 105^0C, W_{600} – weight at 600^0C, W_{C1} – weight of crucible

Moisture content = 100 - T_S

The biological oxygen demand is calculated as,

Final DO - Initial DO * dilution factor, where dilution factor taken was 500 (1ml of sample in 500 ml of water).

Here, DO – dissolved oxygen

The biological oxygen demand of apple pomace and pine needles came out to be 2660 mg/L and 2975 mg/L. The dissolved oxygen of apple pomace and pine needles was 6.37 mg/L and 6.22 mg/L which was reduced to 1.05 mg/L and 0.27 mg/L after incubation in BOD incubator.

For chemical oxygen demand, the following procedure is followed,

a) In reaction vessel, take 2ml sample, 30ml silver sulphate sulphuric acid solution, 10ml of potassium dichromate, 1gm mercuric sulphate.
b) Titrate the surplus potassium dichromate with the standard ferrous ammonium sulphate (0.1N) using 5 drops of ferroin indicator in the same flask with 40ml distilled water. The end point colour changes to reddish brown from yellow.

COD = (blank reading - sample reading) * N OF FAS * 8000 / Dilution factor (20)

Chemical oxygen demand came out to be 3280 mg/L and 6000 mg/L, respectively. The gas composition in percentage was measured using biogas sensor 5000 Geotech gas analyzer 9QED Environmental System, Coventry, UK).

Properties	Apple pomace	Pine needles slurry
Total solids	17.26%	19.75%
Volatile solids	16.86%	18.07%
VS/TS ratio	97.6%	91.3%
BOD	2660 mg/L	2975 mg/L
COD	3280 mg/L	6000 mg/L
Dissolved oxygen (DO)	6.37 mg/L	6.22 mg/L
Moisture content	82.74%	80.21%
Fixed Solids	0.4%	1.68%

Table 3.1) Nature of substrate.

3.5 Measurement of Biogas

The biogas was volumetrically measured. The daily increase in the gasholder was properly monitored from four different directions around the holder's periphery, and the average was taken as the rise of the gasholder. As a result, the volume of the gas was calculated. Biogas sensor 5000 Geotech gas analyzer was used to determine the composition of Biogas (O_2, CO_2, H_2S, and so on) (QED Environmental System, Coventry, UK) as shown in figure 4.1.

3.6 Analytical Method

Before beginning the studies, the first and most important step was to determine the substrate's composition in terms of determining its biodegradable percentage using analytical criteria. Aside from that, numerous analytical criteria were used to establish the characterization of influent and effluent slurry. The following are the parameters: MC, TS, VS FS, pH, temperature, BOD, and COD. Among these parameters, pH, TS, VS, VS, and MC were determined using standard instruments and procedures, as recommended by APHA (2005) [58]. A digital/electronic thermometer was used to determine the daily ambient temperature.

3.7 Experimental Procedure

One of the goals of this research was to see if utilizing apple pomace and pine needles for biogas production was feasible. The working approach of the experiments is presented in this part.

3.7.1 Feeding, and Working Details of the Reactor

The anaerobic reactor was not fed until all of the anaerobic bacteria were completely acclimated. The initial feeding was carried out once the anaerobic environment had been created within the reactor. The feedings were spaced out across a five-day period. The substrate was manually crushed and reduced to a particle size of roughly 1-2 mm before being combined with water to form a homogeneous slurry before each feed. Daily temperature (ambient and within the reactor), pH, and amount of biogas created were recorded from the day of feeding until the day of the following feeding. The OLR was held constant throughout the feasibility study, at 0.04 VS/L/d. The amount of biogas produced (in L) was measured volumetrically. Biogas composition was determined by analyzing the sample for CO_2, CH_4, H_2S, and O_2 with the help of a biogas sensor.

The digesters were named as D1, D2, D3 and D4. Substrate was added according to OLR of 0.04 g VS/L/day. The mode of operation was batch where substrate was added every 5 days as given-

D1- 47.4 g of apple pomace

D2- 44.27 g of pine needle slurry (in ratio 1:5 made by mixing 7.42g pine needles in 36.85 L of water)

D3 (90% apple pomace + 10% pine needle)- 42.70 g of apple pomace and 4.43 g of pine needle slurry (0.7 g pine needle + 3.69 L water)

D4 (75% apple pomace + 25% pine needles)- 35.58g of apple pomace + 11.06 g of pine needle slurry (1.84 g pine needle + 9.22 L water)

OLR was kept constant during the study.

Chapter 4

Results and discussion

4.1 Characteristics of Inoculum and Substrate

The quantity of moisture present in the waste sample i.e. apple pomace and pine needles, has a significant impact on the treatment techniques that will be used. Ways such as incineration, combustion, or pyrolysis, among others, cannot handle wastes with high moisture content, but AD is one of the most appropriate method for waste treatment.

4.2 Gas Production its Composition

The amount of biogas produced in the digesters was calculated by increment in length of gas holding cylinder. The biogas produced in four weeks was 6973.21 cm^3, 15,861.60 cm^3, 25,388.4 cm^3 and 9,674.11 cm^3 in digester 1, 2, 3 and 4 respectively. The highest amount of biogas is produced in digester 3 which was fed with 90% apple pomace and 10% pine needles slurry and least biogas was produced in digester 1 with apple pomace. Since apple is acidic in nature, the less production may be due to slight accumulation of volatile fatty acids. Good amount of biogas was produced in digester 2 and digester 4. The gas composition in percentage is given below in table 4.1. The results shows excellent methane content of 84.4% obtained in digester no.3 followed by 82.7, 80.0 and 78.4 obtained in digester no. 2, 1 and 4 respectively.

Digesters	**Methane(CH_4)**	**CO_2**	**O_2**	**H_2S in ppm**	**Others**
D1	80.0	4.0	0.3	9	15.7
D2	82.7	4.0	0.0	2.1	13.3
D3	84.4	4.9	0.1	2.0	10.5
D4	78.4	5.5	0.1	1.9	16.0

Table 4.1 Gas composition of anaerobic digesters.

4.3) Gas Production and its variation with temperature

The enormous fluctuation in biogas generation may be attributed to a number of factors, but one of the most important is temperature. The maximum ambient temperature was recorded as 34.5°C in May 2022, while the lowest temperature was reported as 28°C, respectively, throughout the experiment. Biogas production is majorly affected by temperature of anaerobic digesters. The current study was carried out in natural mesophilic temperature conditions. Digester 1, 2, 3 and 4 had minimum noted temperature of 29, 28, 29 and 29^0C respectively and maximum temperature as 34, 32.5, 34 and 34.5^0C respectively. The daily changes in temperature of digesters were observed for 28 days as shown in figure 4.2.

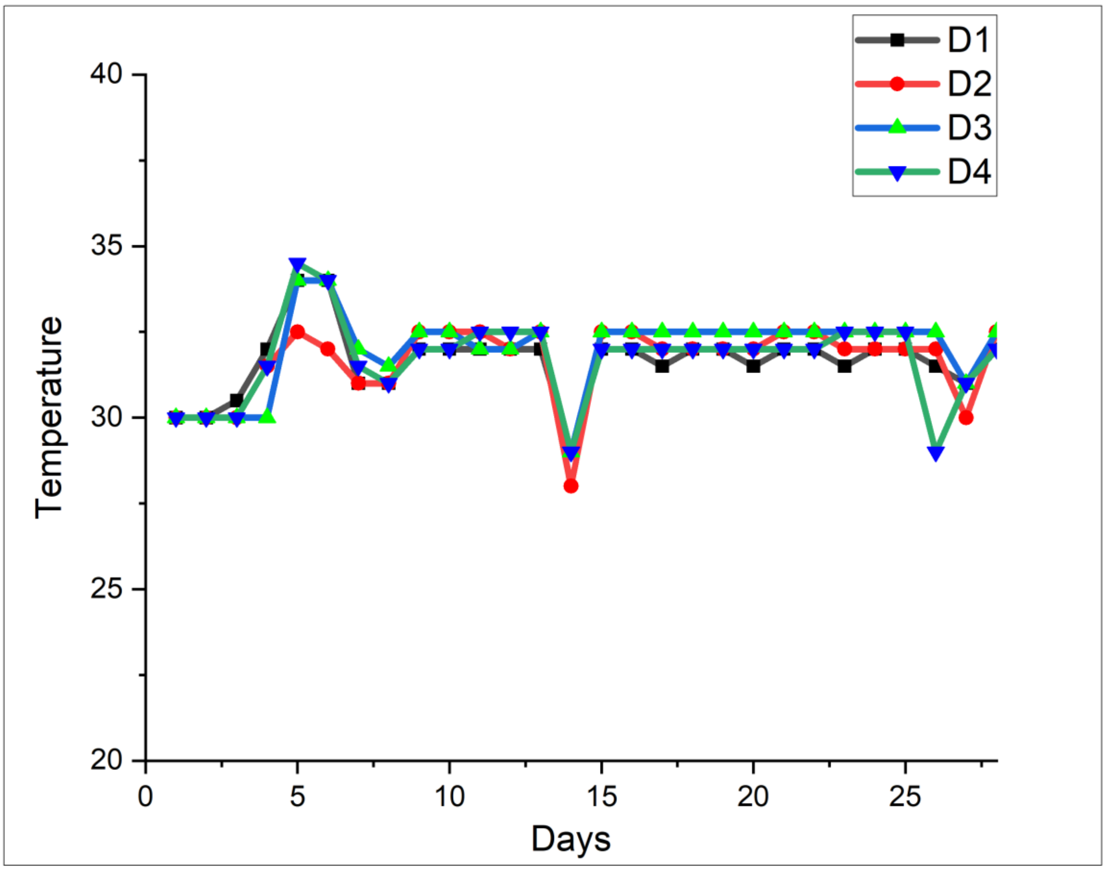

Figure 4.2) temperature variation with time from month April (12/4/22) – May (9/5/22)

4.4) Gas Production and its variation with pH

pH is major factor in anaerobic digestion affecting microbial activity. pH of 6.3-7.8 is appropriate for anaerobic digestion [25]. Digester no. 1 (D1) fed with apple pomace had minimum pH of 6.01 and maximum pH of 6.30, the drop in pH was due to acidic nature of apple pomace. Digester no. 2 (D2) fed with pine needles slurry had minimum pH of 6.10 and maximum pH of 6.44. Digester no. 3 (D3) having 90% apple pomace and 10% pine needles slurry had minimum pH of 6.34 and maximum pH of 6.67. This digester with most appropriate pH have been most effective in working. Digester no. 4 (D4) fed with 75% apple pomace and 25% pine needles had minimum pH of 6.20 and maximum pH of 6.38. In case of pH drop, calcium hydroxide i.e. lime was added to balance acidity. The daily changes in pH of digesters were observed for 28 days as shown in figure 4.3.

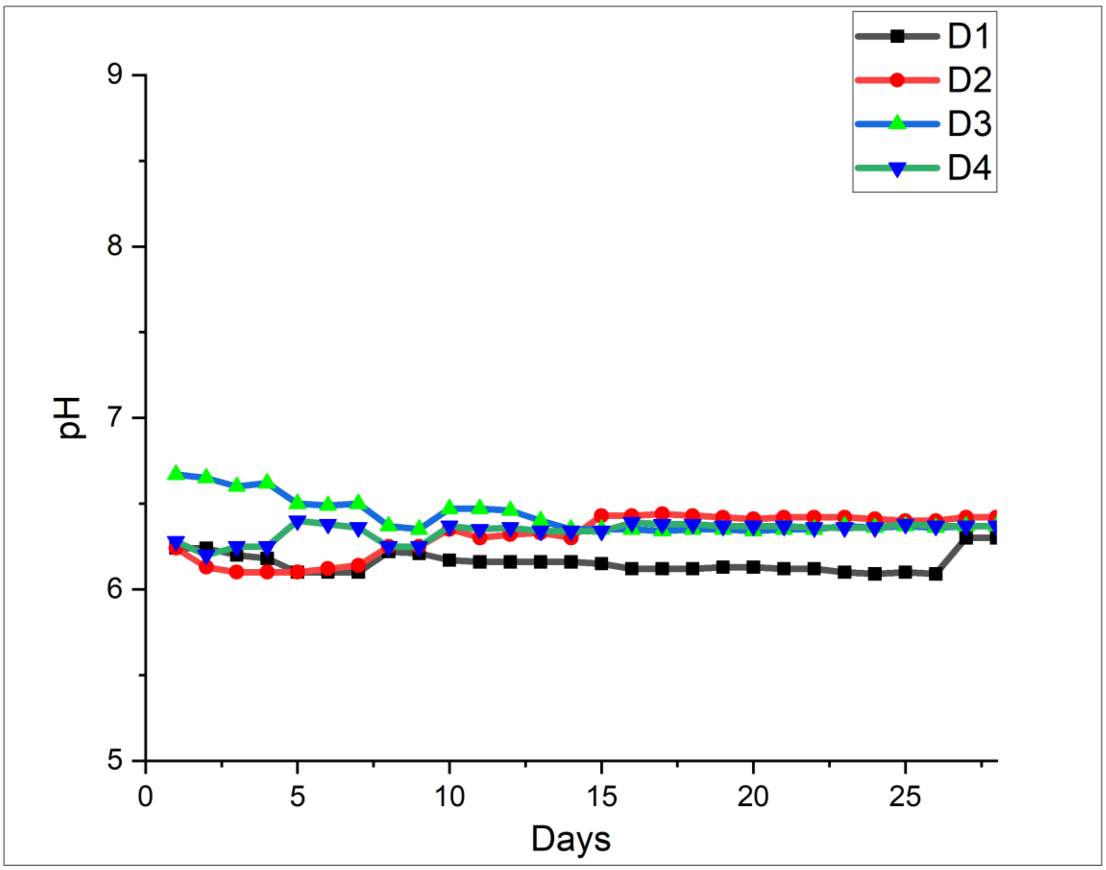

Figure 4.2) pH variation with time from month April (12/4/22) – May (9/5/22)

4.5) Kinetic and mathematical modeling

Kinetic and mathematical models are used to study the performance of anaerobic digestion process. Certain models aid in determining crucial AD parameters such as cumulative methane production (Po in L/g VS), hydrolysis rate constant (k in day^{-1}) and maximal biogas output (P in L/g VS). The model used in current study is first order kinetic model referred as FOM. This model helps us determine the above parameters. The following equation 3.1 describes FOM,

$$P_O = P\,(1 - \exp(-k.t)) \qquad (4.1)$$

t is biogas accumulation time in days, here k is the major parameter obtained.
Pine needle being a lignocellulosic waste will have lower k value than apple pomace [59].

4.6) Conclusion

The experiment was conducted for a period of four weeks (28 days) at ambient temperature. The objective was to determine the methane content and biogas yield from the co-digestion of apple pomace and pine needles at varying atmospheric conditions. The major findings of the study were,

1) The amount of biogas produced by apple pomace (D1), pine needles slurry (D2), 9:1 apple pomace and pine needles slurry (D3) and 7.5:2.5 apple pomace and pine needles slurry (D4) was 6.97 L, 15.861 L, 25.388 L and 9.674 L, respectively.
2) D3 having 90% apple pomace and 10% pine needles slurry gave highest amount to biogas, it was shown to have most appropriate pH range of 6.35-6.67.
3) D3 showed good methane content of 84.4% followed by 82.7%, 80.0% and 78.4% in D2, D1 and D4, respectively.

The results will be helpful for those who work in biogas production areas. Also the study is beneficial to those who are willing to make efficient utilization of wastes i.e. apple pomace and pine needles. Daily pH and temperature variations were observed during study which were shown to have great impact on biogas production. The study focuses on environmental friendly ways for waste utilization and bioenergy production.

Conference Publications

Smriti Gaba, Aaina Sharma, Karam Dass, Ashish Kumar, Sudhir Kumar. Biogas Production using one-stage reactor. In a National Conference on Current Scintific Innovations and Research in Plant Biology at Eternal University, Baru Sahib, Himachal Pradesh (27-28 May, 2022)

Smriti Gaba, Sudhir Kumar, Ashish Kumar. Sustainable management of biomass for energy generation. A Virtual International Conference on Technological Intervention in renewable energy for Sustainable Environment, CESTRD, Jaypee University of Information Technology, Himanchal Pradesh (24-25 Nov, 2021.

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