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Assessment of Sustainable Biogas Production from Co-Digestion of Jatropha De-Oiled Cake and Cattle Dung Using Floating Drum Type Digester under Psychrophilic and Mesophilic Conditions

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Abstract: Biodiesel is an emerging alternative fuel that is generally made from edible and non-edible oilseed crops. *Jatropha curcus* has a high potential for producing biodiesel, which yields 25–35% oil along with 75–65% solid byproduct, generally called a de-oiled cake. The present manuscript deals with the co-digestion of Jatropha de-oiled cake along with cattle dung (1:1 ratio) for biogas production in a floating-type biogas digester. The experimental study was carried out in a modified KVIC biogas plant of 6 cubic meter capacity for 60 days' retention time under psychrophilic and mesophilic temperature conditions. During all the experiments, the total solid content of the slurry was maintained fixed at 10–12% by mixing 10 kg Jatropha de-oiled cake and 10 kg cattle dung with 80 kg water. The experimental results showed that the average specific biogas production of Jatropha de-oiled cake and cattle dung slurry was observed to be 0.216 m^3/kg *TS*, 0.252 m^3/kg *VS* and 0.287 m^3/kg *TS*, 0.335 m^3/kg *VS*, respectively, under the aforementioned conditions. Moreover, the biogas methane concentration was observed to be 62.33% to 69.16% under mesophilic temperature conditions compared to the psychrophilic temperature conditions, 65.21% to 69.15%, respectively. Furthermore, the average total volatile solids mass removal efficiency of feeding material in the abovementioned process was 7% higher under mesophilic temperature conditions than psychrophilic temperature conditions. Additionally, the results indicated that a total 588.8 kg of input volatile solids produced a total of 7306.56 MJ/m^3 and 5177.88 MJ/m^3 energy in 60 days under psychrophilic and mesophilic temperature conditions. On the basis of the results, it is concluded that Jatropha de-oiled cake may be a superior solution for improving biogas quality and composition as well as a value-added product, i.e., organic manure.

Keywords: Jatropha; de-oiled cake; biogas; anaerobic digestion; methane

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1. Introduction

Energy is the backbone of a country's technological and economic progress. Energy usage and demand are increasing on a daily basis as a result of industrialization, urbanization, and modernization, placing industrialized and developing countries in catastrophic energy situations in the future [1–3]. More than 80% of worldwide primary energy consumption is met by petroleum-based fuels, with the transportation sector accounting for up to 60% of overall demand [4]. However, the long-term viability of fossil fuels remains a key concern in terms of economics, the environment, and ecology. Additionally, the burning of fossil fuels releases carbon dioxide and other greenhouse gases, which have major environmental consequences and lead to climate change and global warming [5–8]. The primary issues that have motivated researchers to develop new alternative and renewable energy sources are depleting fossil fuel supplies owing to over-exploitation, price fluctuations, and the escalating consequences of fossil fuel consumption. In developing nations such as India, solar, wind, hydro, and biomass energy have all been explored and utilized as green and sustainable energy sources [8–12]. Biofuels and bio-products made from plant biomass have the potency to replace conventional fossil fuels. This might be because the CO_2 emitted during burning equals the CO_2 absorbed by the plant during photosynthesis, resulting in no net CO_2 increase in the environment, because bioresources are known to have a low biogenic carbon factor.

Biomass has been utilized as a fuel source since humans discovered how to produce fire, and it was the major source of energy until the twentieth century, when fossil fuels became readily available [13,14]. Biomass is still also a major source of energy for the world's poorest people. Biomass can be converted into liquid fuels (e.g., biodiesel, bioethanol), gaseous fuel (e.g., biogas, syngas), and solid fuel (e.g., bio-coal, biomass briquettes) depending on conversion methods [3,15–18]. Biogas has a large renewable energy potential and a wide range of applications in today's energy-intensive world. Biogas is generally comprised of primarily 55–75% methane and 25–45% carbon dioxide, along with a small quantity of hydrogen and hydrogen sulfide [19–21]. It is produced by anaerobic digestion or fermentation of biodegradable materials such as biomass, manure, sewage, municipal waste, green waste, plant material, and energy crops. In addition, oil extracted wastes, generally called de-oiled cakes, are emerging feedstock for biogas production and are gaining attention worldwide [20,22,23].

According to the Food and Agricultural Organization's (FAO Food's) Outlook November 2020 report, the worldwide output of oil cakes and meals is expected to reach 158.7 million tons in 2020–2021 [20]. Therefore, it is necessary to properly manage it. Various researchers have carried out experiments to produce biogas from the de-oiled cake. For example, Chandra et al. experimented with a 5 L glass fermenter using Jatropha seed cake and produced 265 L/kg biogas with a concentration of 65% bio-methane [24]. Deshpande et al. generated biogas from the de-oiled cake of mahua and hingan oil cakes in the range of 198 to 233 L/kg of biomass [22]. Raheman et al. investigated the influence of C:N and total solid content on biogas production yield from Jatropha de-oiled cake and found that the optimal *TS* and C:N ratios for maximal biogas generation were 15–20% and 22:1 to 27:1, respectively [25]. Jha et al. studied the biogas production potential of rice bran de-oiled cake and achieved an average specific biogas yield of 0.470 L/g *TS* and 0.547 L/g *VS* with an average specific methane production of 0.232 L/g *TS* and 0.270 L/g *VS* [26]. Gupta et al. conducted anaerobic digestion of *Madhuca indica* de-oiled cake for biogas production and discovered that combining 50% hot water detoxified MC with 50% CD resulted in the highest biogas output of 442 L/kgTS with a methane concentration of 58.5–60% [27]. Jabłonski et al. studied the impact of different pretreatment methods on biogas production from Jatropha de-oiled cake [28]. Barik et al. performed anaerobic digestion of de-oiled seed cake of Karanja (SCK) with cattle dung (CD) by mixing it in flowing ratios of 75:25 (S1), 50:50 (S2), 25:75 (S3), and 0:100 (S4) on a weight basis and found that the combination of 25:75 (S3) resulted in the best yield of methane (73% CH_4) [29].

However, there are many factors that affect biogas yield, but temperature plays a crucial role in bio-methane production. Psychrophilic (>25 °C), mesophilic (32–42 °C), and thermophilic (50–57 °C) temperatures can be employed in a biogas reactor depending on the microorganism group used in the process [30]. Most of the study is carried out in either psychrophilic or mesophilic conditions [23,25,29,31–34]; however, we found no study that explored bio-methane production potential from Jatropha de-oiled cake and cattle dung under both psychrophilic and mesophilic temperature conditions. Hence, the main purpose of this study is to see how well Jatropha de-oiled cake with cattle dung can generate biogas in the summer and winter seasons. Therefore, the co-digestion of 50% cattle dung and 50% Jatropha de-oiled cake was carried out in a 6 m^3 floating drum-type reactor for 60 days retention time under the aforementioned conditions. Total biogas production, specific biomethane production, biogas composition, and total volatile removal efficiency of the process were determined on a daily basis.

2. Materials and Methods

In this section of the work, the materials utilized for the specified experiments, as well as the estimation of parameters, are described.

2.1. Feedstock for Experiments

Jatropha de-oiled cakes (JDC) and cattle dung (CD) were used for co-digestion in this study. Jatropha seeds were obtained from a local trader of Dehradun, Uttarakhand, India. To extract the oil from Jatropha de-oiled cake, a screw press expeller (Make-Azad, Ghaziabad, India) was utilized. The solid residue obtained after oil extraction is called Jatropha de-oiled cake and was utilized for biogas production in this study. Fifty kilograms of seeds resulted in 14.1 L of oil and 33. 2 kg of Jatropha de-oiled cake.

2.2. Characterization of Feedstock

Proximate analysis (total solids, volatile solids, moisture, and ash contents) of the Jatropha de-oiled cakes and cattle dung feedstock were measured using the ASTM D3172-07a standards [7,10]. On the other hand, the ultimate analysis of the elemental composition of the Jatropha de-oiled cakes and cattle dung feedstock was examined using a Thermo Flash 2000 CHNS/O elemental analyzer. Elements such as carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) were examined, and oxygen (O) was calculated by difference from 100 wt.%. In addition, the total lipid content was analyzed using the Soxhlet extraction method, while the protein content of Jatropha de-oiled cake was determined by the Kjeldahl method.

2.3. Preparation of Feed Material

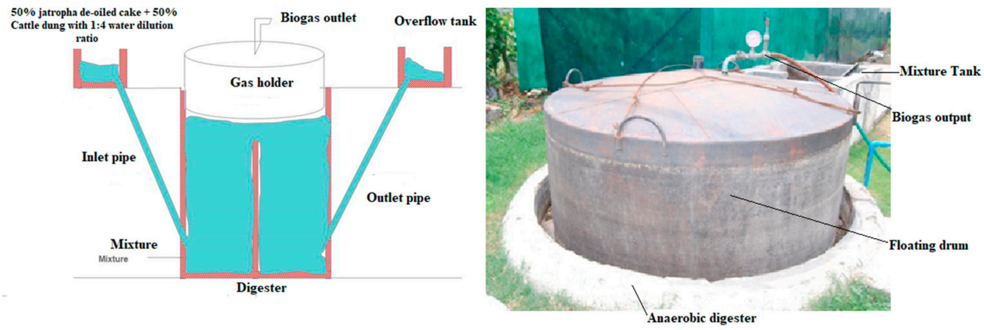
All the experiments were performed in a 6 m^3 floating-type biogas digester running with cattle dung. Before starting the experiments, the feeding of cattle dung into this digester was stopped for two months to ensure that there was no unprocessed cattle dung inside. After that, the Jatropha de-oiled cake and cattle dung were fed into the biogas digester.

To prepare the feedstock mixture (slurry), 10 kg of JDC and 10 kg of CD were mixed with 80 kg of water in a cemented tank constructed nearby the biogas digester. Throughout all of the experiments, the total solid content of the slurry was kept between 10 and 12% for better reaction outcomes. In addition, the pH of the slurry was also checked before feeding to the digester on a daily basis and should be maintained at nearly 7.0.

The slurry was well-mixed before feeding to ensure that it was a homogeneous mixture. The reaction was carried out in semi-continuous mode for 60 days of hydraulic retention time (HRT). At the interval of 24 h, the slurry was fed daily to the digester.

2.4. Experimental Set-Up and Consequent Processes

The digester employed for biogas generation was a 6 m^3 floating-type biogas plant, as depicted in Figure 1. It should be noted that the biogas plant employed in this study was previously fed with cattle dung (CD). A continuous inspection was enabled while making the slurry, and it was manually mixed with enough stirring capacity. The slurry was held at bay for 3–4 h after preparation to ensure that the feeds dissolved and mixed thoroughly. Furthermore, during hydrolysis in a biogas reactor, this mechanism contributes to the breakdown of big molecules into smaller ones. The studies were conducted at ambient temperatures over the summer and winter seasons, with all other parameters (such as slurry loading rate, pH, total solid content, carbon to nitrogen ratio, and retention time) remaining constant. The biogas yield was calculated by measuring the uplift height of the floating drum on a daily basis. The height of the drum was calibrated with the help of a pointer and scale. The pointer was adjusted at zero when there was no biogas inside the drum.



(**a**) (**b**)

Figure 1. (**a**) Schematic diagram of biogas digester, and (**b**) biogas digester used for experiment.

The biogas composition was analyzed with the help of a gas chromatograph (GC), Nucon 5700 series. The GC was equipped with a 2 m long poropak, column, and thermal conductivity detector (TCD). The operating conditions for the GC were: (i) oven temperature, 0 °C; injector and detector temperature, 120 °C. Argon gas was used as carrier gas. GC was calibrated using a standard biogas gas composition, and the sample was analyzed using the normalization technique.

2.5. Biogas Production Analysis

Further, for the analysis of the biogas, the following sets of models were employed at standard temperature and pressure (STP) conditions. STP is configured at 0 °C (273 °F) and one atmospheric pressure.

To determine the daily methane and carbon dioxide production yield, the following equations were used.

$$CH_4^{yield} = \left(\frac{CH_4\ conc}{100}\right).\ BV_0 \quad (1)$$

$$CO_2^{yield} = \left(\frac{CO_2\ conc}{100}\right).\ BV_0 \quad (2)$$

The following equation was used to determine the specific biogas and methane production (per unit TS and VS):

$$BV_0\ Specific\ TS = \left(\frac{BV_0}{DMF.\ TS}\right) \quad (3)$$

where DMF represents the mass of feeding material fed to the reactor daily in kg, and TS is the total solids content in decimals; VS is the volatile solids content.

$$TS_{Specific\ methane\ production} = \left(\frac{CH_4\ yield}{DMF.\ TS}\right) \quad (4)$$

$$TS_{Specific\ methane\ production} = \left(\frac{CH_4\ yield}{DMF.\ VS}\right) \quad (5)$$

The mass of methane and carbon dioxide generated was then taken to be equivalent to the mass of volatile solids removed. During the anaerobic digestion process, volatile compounds are lost when volatile molecules are converted to biogas. The total volatile solids mass removal efficiency was determined using the biogas production rate. In this estimation approach, the quantity of dry biogas obtained was assumed to be equal to the mass of organic material converted into biogas. Throughout the process, the methane and carbon dioxide content of the biogas was measured at one-day intervals. It was presumed that biogas acts like an ideal gas. The generated mass of methane and carbon dioxide was then believed to be equivalent to the mass of volatile solids removed:

$$Total\ VS\ mass\ removed = Mass\ CH_4 + Mass\ of\ CO_2 \tag{6}$$

However, the requirement of the above approach is that the biogas volume and its contents should be accurately measured. The molecular weight of methane and carbon dioxide, as well as dry biogas volume, were then correlated to obtain the total volatile solid mass removed. The following relationship (Equation (7)) was used to obtain the total volatile solid mass removed in the anaerobic digestion process:

$$TVSMRE = \left(\frac{\left(16 \times CH4\frac{Conc}{100}\right) + \left(44 \times CO2\frac{conc}{100}\right)}{22.413} \right) \times \mathrm{BVo} \times \mathrm{DBF} \times 100 \tag{7}$$

where *TVSMR* is the total volatile solid mass removed in kg; DBF is the dry biogas factor. In the above equation, the volume of one mole of ideal gas at STP is 22.413 L. The following equation was used to compute the total volatile solids mass removal efficiency (*TVSMRE*):

$$TVSMRE = \left(\frac{Total\ VS\ mass\ removed}{Insitial\ total\ VS\ mass\ Feed} \right) .\ 100 \tag{8}$$

3. Results and Discussion

3.1. Characterization of Jatropha De-Oiled Cake and Cattle Dung

The Physico-chemical properties of the de-oiled cake and cattle dung were analyzed according to standard methods. It must be mentioned that the mechanical process for oil extraction that was employed (the screw press) was not able to extract all oil from the seeds. As a consequence, the remaining oil content of the Jatropha de-oiled cake was measured using the 'hexane and diethyl ether solvents' by the Soxhlet extraction method. The biochemical composition of the Jatropha de-oiled cake is presented in Table 1.

Table 1. Biochemical composition of Jatropha de-oiled cake.

Substrate	Crude Protein (%, wt/wt)	Carbohydrate (%, wt/wt)	Acid Detergent Fiber (%, wt/wt)	Neutral Detergent Fiber (%, wt/wt)	Lipid Content (%, wt/Volume)
Jatropha de-oiled cake	38.13 ± 2%	23.54 + 3%	6.54 + 1%	8.71 + 1%	7.2 ± 1%

Each measurement was repeated 3–4 times, and it was observed that de-oiled cake contains about 7.2 ± 1% oil on a weight/volume basis. The average crude protein content of the de-oiled cake was 38.13 ± 2%. This de-oiled cake also had 6.27 ± 1% crude fiber and 6.54 ± 1% acid detergent fiber.

Table 2 summarizes the results of proximate analysis of de-oiled seed cakes and cattle dung in terms of moisture, oil, total solids, volatile solids, and non-volatile solids. The results revealed that fresh cattle dung had an approximate moisture level of 84.5% and a total solids content of 15.5 wt %. Furthermore, fresh cattle dung contained around 83.5% volatile solids on a dry basis, with the remaining 16.5% being non-volatile solids. The lower value of non-volatile solid in de-oiled seed cakes is due to the absence of lignin in it. However, the cattle dung has a high content of lingo-cellulosic material [32]. It is also evident from Table 2 that the ash contents of Jatropha de-oiled seed cakes (0.65%) are significantly lower than cattle dung (1.2). On the other hand, Jatropha de-oiled cake proximate analysis showed that it had 6.8% moisture content along with 91.5% volatile solids and 8.5% non-volatile solids.

Table 2. Proximate analysis of cattle dung and Jatropha de-oiled cake.

Material Used for Feeding the Digester	Proximate Analysis of Jatropha De-oiled Cake (ASTM D3172-07a)				
	Moisture Content in %	Total Solids in %	Volatile Solids in % (on Dry Basis)	Non-Volatile Solids in % (on Dry Basis)	Ash Content (in %)
Cattle dung	84.5	15.5	83.5	16.5	1.2
Jatropha de-oiled cake	6.8 ± 0.5	93.2	91.5	8.5	0.65

The ultimate analysis of Jatropha de-oiled cake showed that the content of carbon, nitrogen, and hydrogen elements in Jatropha de-oiled seed cake was higher than in cattle dung. The ultimate analysis of Jatropha de-oiled cake is shown in Table 3.

Table 3. Ultimate analysis of cattle dung and Jatropha de-oiled cake.

Feed Material	Elemental Analysis						C/N Ratio
	C%	H%	N%	P%	K%	S%	
Cattle dung	34.50	4.45	1.63	0.79	1.77	nd	21.1
Jatropha de-oiled cake	44.51	6.90	3.69	2.09	1.68	0.18	12.06

The results showed that Jatropha de-oiled cake had 44.51% carbon compared to cattle dung (34.50%). On the other hand, the hydrogen content of Jatropha de-oiled cake and cattle dung was observed as 6.90% and 4.45%, respectively. Carbon (in carbohydrates) and nitrogen (in protein) are to be in the proper form and concentration for bacteria to grow and function optimally (in proteins). Therefore, nitrogen plays a significant role in biogas production yield. The nitrogen content of cattle dung was observed as 1.63% and 3.69%, respectively, on a dried basis. However, the C:N ratio of Jatropha de-oiled cake was 12.06, which was relatively lower than cattle dung at 21.1. Other elements, including P (phosphorous), K (potassium), and S (sulphur) in Jatropha de-oiled cake are 2.09%, 1.68%, and 0.68%, respectively. The results were in accordance with other studies [25,35]. Based on ultimate, proximate, and chemical composition, it was concluded that JDC has good potential for biogas generation. As shown in Table 1, it also had a good quantity of proteins and lipids that can be used by microbes during the anaerobic digestion process.

3.2. Biogas Production from Jatropha De-Oiled Cake and Cattle Dung under Psychrophilic and Mesophilic Temperature Conditions

The average pH of the feeding slurry was found to be about 6.82 with a 1:4 dilution ratio (DR), as evaluated by a pH meter. According to Jha et al. 2020, most anaerobic microorganisms, particularly methane-forming bacteria, perform best when the pH ranges between 6.8 and 7.1. It is important to note that the amounts of VFAs, ammonium, and alkalinity have a substantial impact on pH. The increase in VFAs causes a pH value decrease; an increase in alkalinity sources, on the other hand, produces a rise in pH value.

Figure 2 illustrates the correlation between daily biogas production yield and retention time for feeding substrate (50% JDC + 50% CD) at a feeding ratio of 9.813 kg VS/day under psychrophilic and mesophilic temperature conditions. The results revealed that the average daily biogas production was observed as 2.40 m^3/day and 3.38 m^3/day under psychrophilic and mesophilic temperature conditions. As shown in Figure 2, the biogas production rate took 10 days to stabilize. Figure 2 indicates that the biogas production rate was relatively low during the early days of the retention period compared to subsequent days. When the hydraulic retention time exceeds five days, it has been reported that the biogas production yield increases as the methane-forming bacteria start to consume the volatile acids quickly.

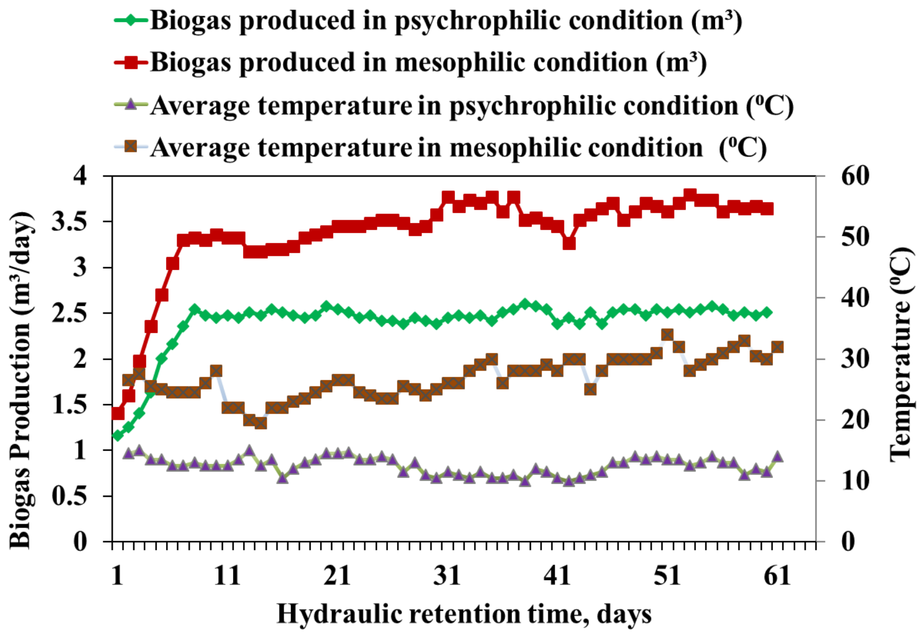


Figure 2. Daily biogas production 50% JDC + 50% CD in psychrophilic and mesophilic temperature conditions.

In psychrophilic and mesophilic conditions, the temperature during anaerobic digestion was found to be in the range of 10–18 °C and 22–35 °C, respectively. Daily observed temperature was the average of the maximum and minimum temperature of that day. The digester performed better in the mesophilic temperature range. Literature also suggests that biogas production increases with increasing temperature, as higher temperature supports methanogenic bacteria's activity [30]. Dehradun is a city in which nights are colder than days, and bacteria are active only during day hours. Thus, biogas production is greater during the daytime, even in the summer.

The biogas production was found to be lower in the winter, as the temperature drops below 10 °C during the night, which results in the inactivation of methanogenic bacteria activities; therefore, total biogas production is reduced, as was witnessed in the present case. Temperature fluctuations also affect bacterial activity, and therefore, biogas yield was significantly lower under psychrophilic than mesophilic temperatures.

As shown in Figure 2, the daily biogas output increased steadily for the first 10 days before stabilizing. Methanogenic bacteria are responsible for this. These kinds of bacteria struggle to survive in their fresh environment for the first ten days because they are unable to adapt to the conditions, resulting in low consumption of volatile substances and lower microbe activity. This is also due to the toxic nature of Jatropha de-oiled cake, which hinders the normal growth and activity of biogas-producing bacteria on the feeding substrate [25,35]. Furthermore, Figure 3 shows the variation of daily biogas production per kg *TS* and *VS* under mesophilic and psychrophilic conditions against the feeding of 10.86 kg total solid per day and 9.813 kg of volatile solid per day. It was observed that biogas production per kg *TS* and *VS* was 0.311 m^3 per day and 0.355 m^3 per day in mesophilic temperature conditions, while it was 0.220 and 0.251 m^3 per day in psychrophilic conditions. Biogas production was three times higher with 50% JD + 50% CD in comparison to fresh cattle dung. This is due to the reason that under mesophilic conditions, the substrate temperature range was observed to vary from 20–35 °C, which is considered ideal conditions for methanogenic bacteria activity. For 6 m^3 biogas production, 50 kg of 50% JD + 50% CD was required, in comparison to 150 kg of cattle dung.

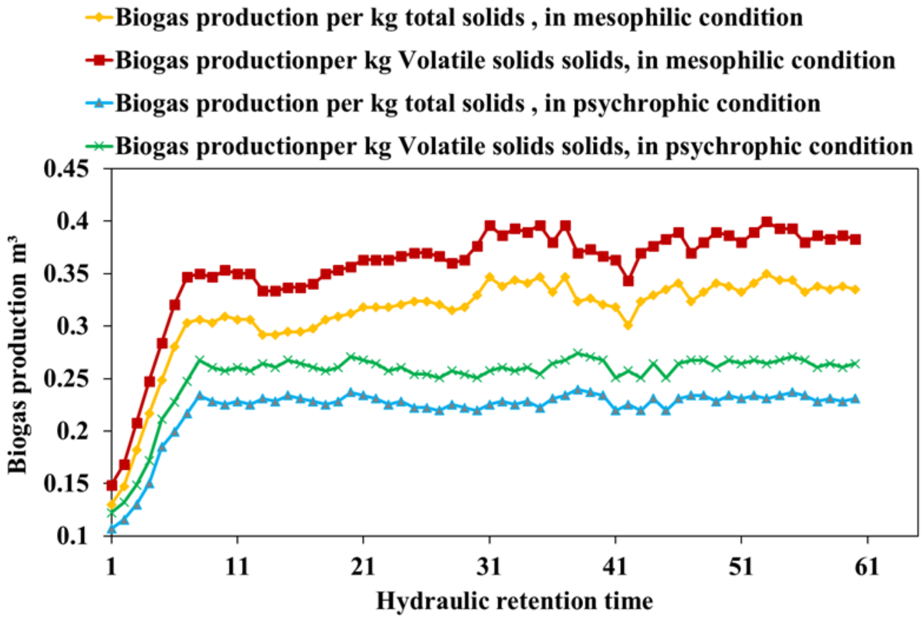


Figure 3. Daily biogas production per Kg *TS* and *VS* 50% JDC + 50% CD under psychrophilic and mesophilic conditions.

3.3. Specific Biogas Production Rate from Jatropha De-Oiled Cake and Cattle Dung under Psychrophilic and Mesophilic Temperature Conditions

Specific biogas production represents the daily biogas produced against daily feed volatiles or total solids at STP, which is calculated by dividing daily volatile or solids feeding to the digester by the daily biogas production at STP. The specific biogas production yield per unit *TS* and per unit *VS* from 50% JDC + 50% CD is shown in Figure 4. The results revealed that specific biogas production yield with 50% JDC + 50% CD was observed to be 0.101–0.229 m^3/kg *TS* and 0.112–0.254 m^3/kg *VS* under psychrophilic temperature conditions, while the mesophilic temperature conditions showed 0.118–0.321 m^3/kg *TS* and 0.131–0.355 m^3/kg *VS* specific biogas production. The maximum specific biogas yield was 0.355 m^3/kg *VS* under mesophilic conditions compared to psychrophilic temperature conditions (0.254 m^3/kg *VS*). Furthermore, the average specific biogas production yield was recorded as 0.211 m^3/kg *TS* and 0.234 m^3/kg *VS* in psychrophilic temperature conditions and 0.284 m^3/kg *TS* and 0.313m^3/kg *VS* in mesophilic temperature conditions.

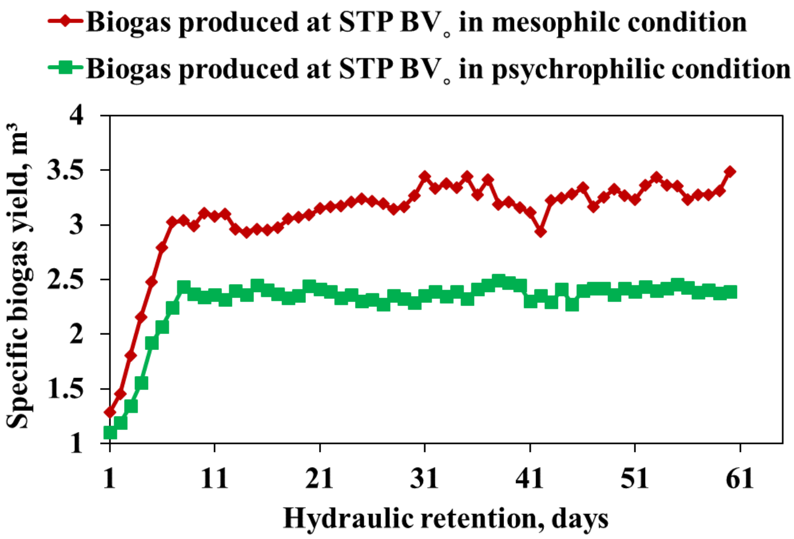


Figure 4. Specific biogas production with 50% JDC + 50% CD under psychrophilic and mesophilic temperature conditions.

3.4. Biogas Composition from 50% JDC + 50% CD under Psychrophilic and Mesophilic Temperatures

Biogas composition was analyzed by a gas chromatograph (GC) and is illustrated in Figure 5. The results showed that methane and carbon dioxide varied from 62.33% to 69.16% and 34.58% to 28.55%, respectively, under psychrophilic temperature conditions, while in mesophilic temperature conditions, methane and carbon dioxide content was recorded in the range of 69.15 to 65.21% and 32.21% to 28.55%, respectively. The average methane, carbon dioxide, nitrogen, and hydrogen sulfide content over 60 days retention period were 65.53%, 31.40%, 1.66%, and 1.36%, respectively, in psychrophilic temperature conditions and 66.60%, 30.58%, 2.01%, and 0.9356% in mesophilic temperature conditions. In both psychrophilic and mesophilic temperature conditions, the methane content in the biogas from 50% JDC + 50% CD was significantly higher than the biogas from cattle dung. This is because of the presence of more lipid and protein content which, under anaerobic digestion, results in more methane content released into the atmosphere (70–84%) [33,34].

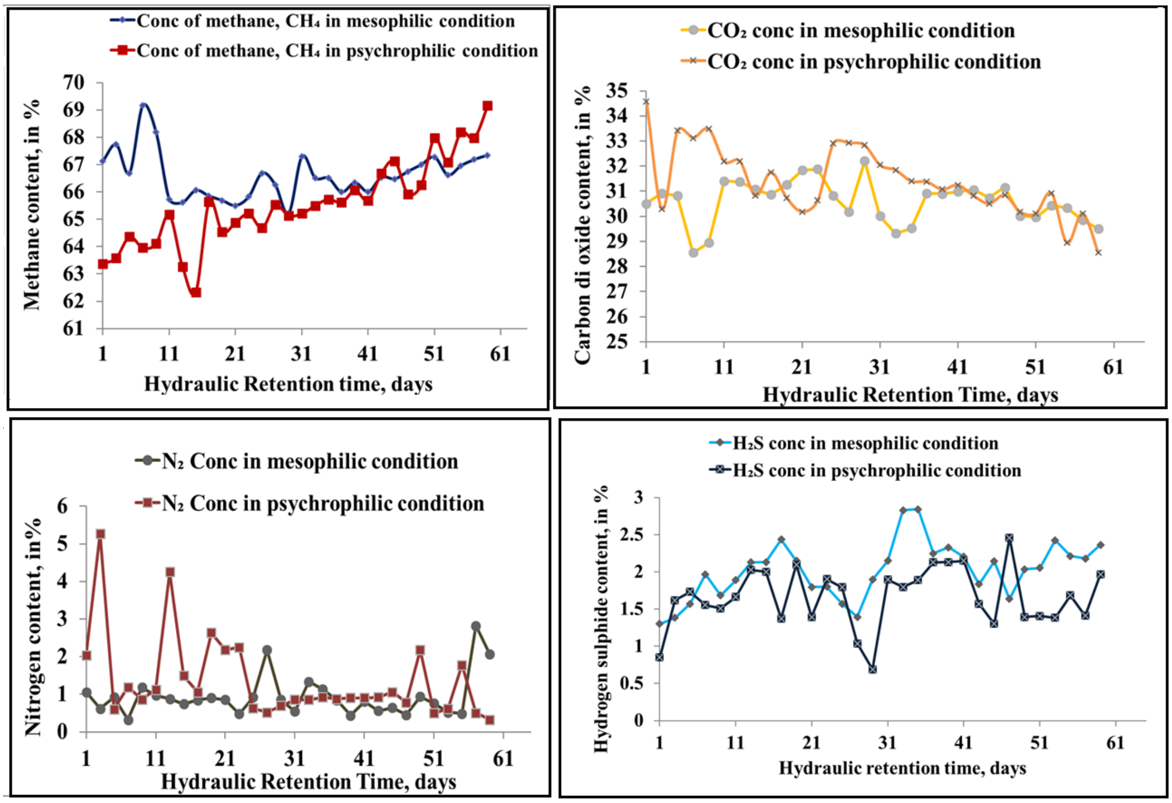


Figure 5. Biogas composition produced from 50% JDC + CD under psychrophilic and mesophilic temperature conditions.

3.5. Specific and Cumulative Methane Production Rate from 50% JDC + 50%CD under Psychrophilic and Mesophilic Temperatures

Figure 6 demonstrates the specific methane production yield with respect to *TS* and *VS* from 50% JDC + 50% CD under psychrophilic and mesophilic temperature conditions. Specific methane production yield was examined by dividing daily CH_4 yield by daily volatiles or total solids fed to the digester. The results revealed that the specific methane production yield was in the range of 0.66–0.154 m^3/kg for *TS* and 0.071–0.170 m^3/kg for *VS* through the 60-day retention time under psychrophilic temperature conditions while it was 0.080–0.213 m^3/kg *TS* and 0.088–0236 m^3/kg *VS* in mesophilic temperature conditions. On the other hand, it was also observed that the biomethane yield increased with increasing temperature.

Furthermore, it was observed that the overall specific methane production yield was 188 m^3/kg *TS* and 208 m^3/kg for *VS* under mesophilic temperature circumstances, whereas in psychrophilic temperature conditions, 0.137 m^3/kg *TS* and 0.156 m^3/kg *VS* were obtained. Because methanogenic bacteria are more active under mesophilic conditions than psychrophilic conditions, the variation of the average methane content in the biogas produced from 50% JDC + 50% CD was marginally higher in mesophilic temperature than psychrophilic temperature conditions. On the other hand, the cumulative bio-methane was determined to be 202.96 m^3 and 143.83 m^3 correspondingly, with a total of 588.8 kg of input volatile solids in psychrophilic and mesophilic temperature conditions. This is shown in Figure 7.

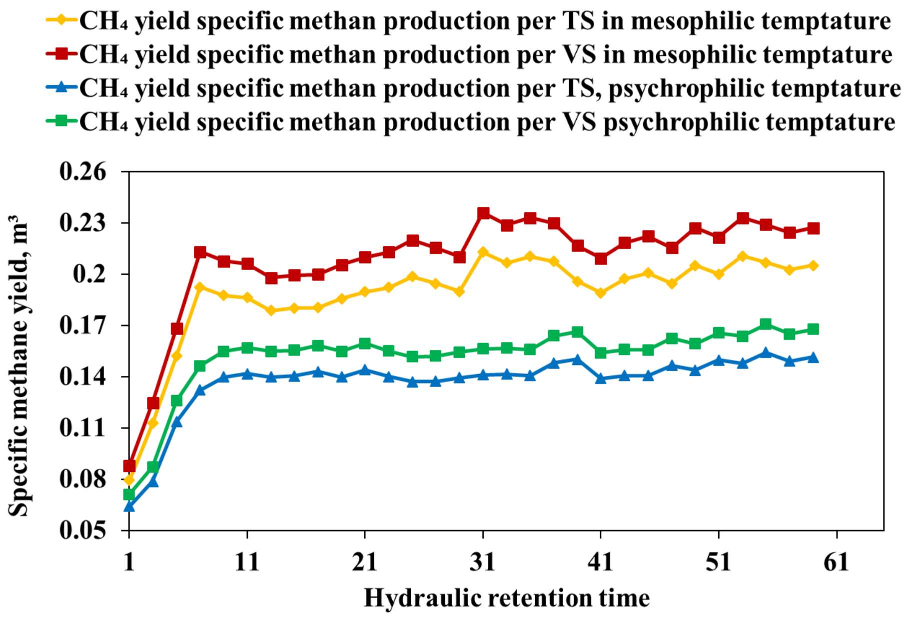


Figure 6. Specific methane yield of 50% JDC + 50% CD under psychrophilic and mesophilic temperature conditions.

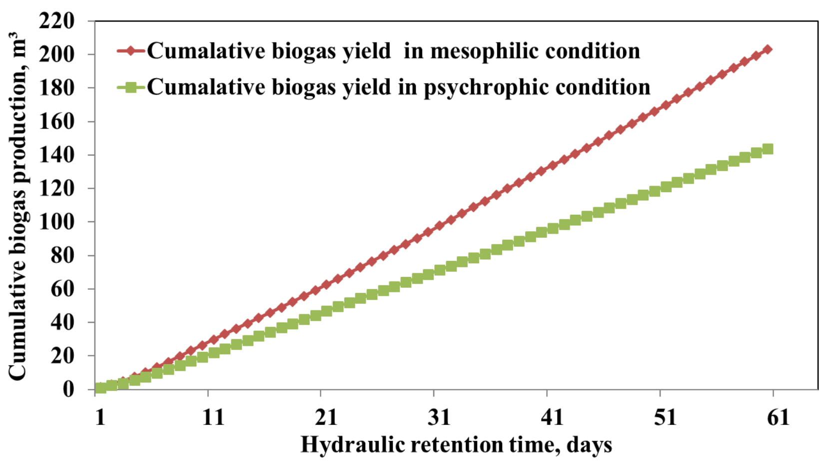


Figure 7. Cumulative methane yield 50% JDC + 50% CD under psychrophilic and mesophilic temperature conditions.

3.6. Total Volatile Solid Mass Removal Efficiency 50% JDC + 50% CD under Psychrophilic and Mesophilic Temperatures

In most cases, there was a significant increase in biogas yield proportional to the amount of organic waste removed. Generally, total volatile solid mass removal efficiency (TVSRE) depends on the community of bacteria present in the digester, pH of the slurry, C/N ratio, loading rate, temperature, retention time, and total moisture content. The focus of this study was to investigate the bio-methane production potential from Jatropha de-oiled cake in summer and winter conditions in hill areas. Hence, pH, C/N ratio, loading rate, retention time, and total moisture content were kept constant, and the study was carried out in semi-continuous mode. TVSRE during anaerobic digestion of 50% JDC + 50% CD under psychrophilic and mesophilic temperatures with respect to retention time is depicted in Figure 8. The results showed that TVSRE of 50% JD + 50% CD was observed from 12.49 to 33.13% under mesophilic temperatures compared to psychrophilic temperature conditions (11.62–24.91%). The average TVSRE of 50% JD + 50% CD substrate was recorded as 30% and 23% in mesophilic and psychrophilic temperature conditions, which was lower than the results reported in [32]. This may be due to the lower temperature conditions in the Dehradun region where the experiment was performed. Furthermore, the average TVSRE of 50% JD + 50%CD was observed to be 7% higher in mesophilic temperature conditions than in psychrophilic temperature conditions. Moreover, Jatropha seed cake has a higher biodegradability in summer (mesophilic temperature conditions) due to the more suitable temperatures for methanogenic bacteria [13,36].

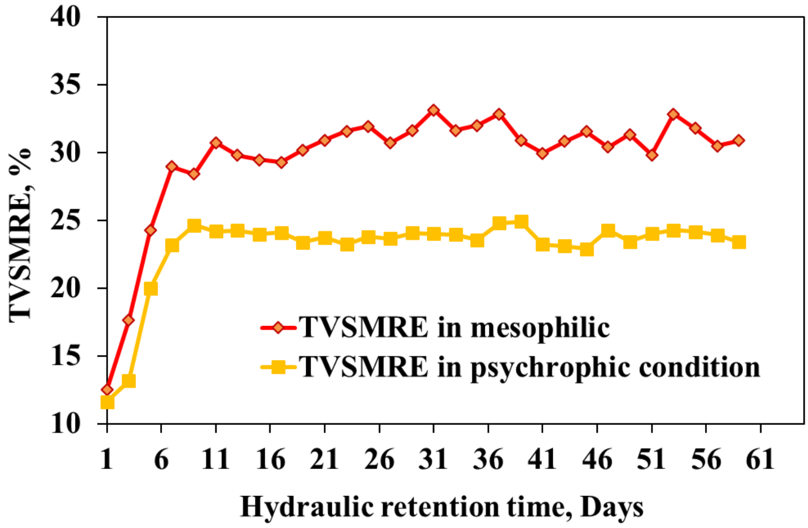


Figure 8. TVSMRE of 50% JD + 50%CD under psychrophilic and mesophilic temperature conditions.

4. Conclusions

In this work, the designated environments of psychrophilic and mesophilic temperature conditions for biogas production are mentioned. Furthermore, the importance of co-digestion with 50% Jatrophas de-oiled cakes (JDC) and 50% cow dung (CD) was studied. The proximate and ultimate analysis showed that JDC had a significant amount of volatile solids, confirming its feasibility for biogas production. The overall biomethane was examined to be 202.96 m^3 and 143.83 m^3 under psychrophilic and mesophilic temperature conditions, respectively, against a total 588.8 kg of input volatile solids. Co-digestion of JDC and CD also resulted in a biomethane concentration under both psychrophilic and mesophilic temperature conditions. Furthermore, the average TVSRE of 50% JD + 50% CD substrate was recorded as 30% and 23% in mesophilic and psychrophilic temperature conditions. It is estimated that about 8 kg of 50% JD + 50% CD was required to produce 1 m^3 biogas in comparison to 25 kg of cattle dung. Under the future scope of the work, the mixing ratio is proposed to be varied along with the addition of biochar and some nanocomposite, and a point of optimization can be modeled for the purpose of understanding large-scale production.

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