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Synergistic Influence of Inoculum Type and Laterite Powder on Anaerobic Digestion Kinetics of Canola Straw

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ABSTRACT

The presence of low nutrient content in the lignocellulosic biomass, such as canola straw (CS), limits its anaerobic biodegradability. Therefore, the main focus of the study is to enhance the nutrient content during anaerobic digestion (AD) of CS. For this purpose, three different inoculum sources such as anaerobically digested manure (ADM), acclimatized sludge (AS), and mixed inoculum (MI), and different concentrations of laterite powder (2, 4, 6, 8, and 10%) were added to enhance the batch AD of CS. Results of the study revealed that the reactor inoculated with ADM performed better, and 15.23% and 10.31% higher biogas yields were observed from the reactors inoculated with AS and MI. Moreover, the 2% addition of laterite powder and ADM as inoculum produced the highest biogas yield of 602 NmL/gVS with a 76.4% VS reduction due to the synergistic effect. In addition, reactors showed better buffering capacity and stability in terms of volatile fatty acids to alkalinity ratios due to the addition of laterite powder during AD of CS. Furthermore, characterization of laterite revealed the presence of an iron source, which created the favourable environment for methanogenesis due to direct interspecies electron transfer (DIET). Biokinetic parameters revealed that the modified Gompertz model (MGM) reproduced the biogas production data. In conclusion, AD of CS may be enhanced by using good-quality inoculum and the addition of lateritic mineral. The addition of microbially active inoculums and laterite powder as a nutrient source may also enhance the anaerobic digestate quality and may be used as fertilizer.

1. Introduction

Pakistan is considered an energy-stressed country and is facing several problems due to the increase in energy demands [1]. Therefore, to overcome the power crisis, different renewable and sustainable energy alternative options are under consideration. However, promoting renewable bioenergy alternatives might play a crucial role. Renewable bioenergy is considered as the fourth largest resource of energy in the world as reported in literature [2]. Conversely, the rising global renewable energy demand and supply has intensified research into the sustainable use of waste agricultural biomass (WAB) for biogas production. Anaerobic digestion (AD) is considered as promising renewable alternative energy technologies that have potentially useful and eco-friendly transformation of WAB into biogas production, which is mostly composed of carbon dioxide (CO_2) and methane (CH_4). As, AD helps in reducing emissions of greenhouse gases, thus improving the management of WAB. On the other hand, operating factors, microbial community makeup, and substrate properties all have an impact on AD performance [3].

In agricultural regions like Pakistan, canola straw (CS), which is a byproduct of growing Brassica napus, makes up a considerable amount of WAB. Following the harvest of canola seeds, farmers usually set fire to CS in open fields. Noonari et al. [4] reported in their study that canola is an important oilseed crops with sunflower and soybean which has a substantial amount of organic matter. The crystalline cellulose structure with low carbon-to-nitrogen ratio and high lignocellulosic complexity with higher volatile solids (VS) contents and organic carbon (OC) in CS make it difficult for methanogenesis and archael populations to degrade during AD [5]. The hydrolysis phase is often regarded as the rate-limiting step of AD, and these refractory characteristics limit it.

For achieving the efficacy of AD process, the microbially active inoculum must have methanogenesis microbes and metabolic activity [6]. The microbial community makeup, enzymatic potential, and adaption to lignocellulosic materials varies across inocula, including digested sludge, rumen fluid, anaerobic granular sludge, and cow dung [6, 7]. Consequently, a diverse microbial population may enhance substrate hydrolysis and methanogenesis by the selection of specific inocula [8]. The use of high-quality inocula can improve biogas production and reaction kinetics by promoting synergistic interactions among hydrolytic, acidogenic, acetogenic, and methanogenic bacteria [9].

Recently, minerals and metal-based conductive materials have gained attention as potential means of improving AD performance [10]. Laterite powder, a naturally occurring iron-rich mineral as reported in a previous study [11]. Therefore, it may provide micronutrients for methanogens and enhance direct interspecies electron transfer (DIET) by promoting the formation of conductive bridges between syntrophic bacteria and methanogenic archaea [12]. The AD process is stabilized due to iron oxides (FeIII/FeII) in laterite, which reduces the accumulation of inhibitory substances such as hydrogen sulfide and volatile fatty acids (VFA). Nonetheless, there is a deficiency in understanding the synergistic link between laterite addition and several inoculum types in lignocellulosic anaerobic digestion.

According to Braga et al. [13], high-quality inoculum has the ability to form anaerobic microbial groups with enzymatic abilities, and the addition of laterite powder may enhance electron transfer processes. Consequently, a more effective and economically feasible AD system for CS might be achieved by combining an effective inoculum source with laterite powder. This synergistic effect has the potential role for enhanced biogas output, lower VS, and improve process stability.

For predicting the AD biokinetic behavior from experimental cumulative biogas output, the modified Gompertz model (MGM) is frequently used. The three stages of biogas yield, including the biogas generation potential, the time spent in the lag phase, and the plateau phase, are represented by the sigmoidal function known as MGM. Important biokinetic characteristics may be simulated using this model, which supports in AD process optimization and prediction. Kainthola et al. [14] and Veluchamy and Kalamdhad [15] are only two of several studies that have used MGM to model the biokinetics of AD reactors.

Gu et al. [16] and Rajput and Sheikh [6] compared various inoculum sources. In a previous study [6], three different inocula were used to determine the organic loadings of the sunflower meal and wheat straw through the digestion of manure, the acclimatization of the sludge and the septic tank sludge. Moreover, these studies also described the impact of different inoculum sources on AD in rice straw and concluded that the inoculum made by manure exhibited the best results. In the case of the AD process, Sicchieri et al. [17] had experimented with numerous sources of inoculums, such as digested dung, sludge, and a mix of the two. They discovered that mixed inoculum (MI) provided them with optimum initial microbial populations. Recently conductive materials are under consideration to promote the process of AD. Tariq et al. [18] discovered that the addition of a minor quantity of the laterite powder (around 0.1-0.3 %) to biochar boosted the biogas generation and improved the quality of the digestate. Other studies, which used magnetite to enhance AD, found that its addition as 8 g to swine dung enhanced biogas recovery. Therefore, there is a dire need to assess various sources of inoculum and different concentrations of laterite powder to enhance the AD of CS. The present study assessed higher concentrations of laterite powder with a good source of inoculum selection to understand the synergistic influence of the inoculums and conductive material on the AD of CS. Therefore, it might be the novel findings to improve the AD of lignocellulosic biomass such as CS.

The aim of this study is to evaluate the synergistic influence of different types of inoculums and laterite powder on the AD performance of CS. In addition, the buffering capacity of batch reactors were also assessed. Moreover, the characterization of laterite powder was also performed in terms of surface morphology through SEM, elemental analysis by X-ray fluorescence (XRF), microscopic examination, and particle size distribution (PSD). Furthermore, the kinetics of biogas production were also performed using the modified Gompertz model (MGM). This research may provide a scientific basis for optimizing the AD of lignocellulosic biomass such as CS through good-quality inoculum selection and mineral addition for sustainable bioenergy production from CS.

2. Materials and Methods

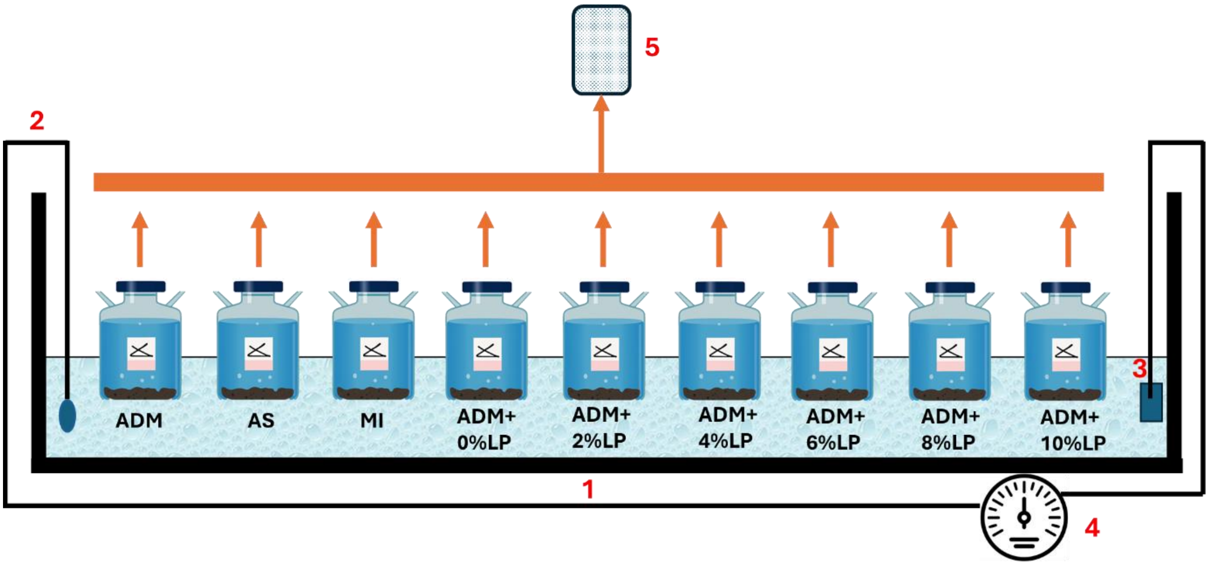
2.1 Materials Collection

Present study used CS as a substrate which was collected from a local farmer within the vicinity of Tando Allahyar, Sindh. CS was crushed to below 5 mm using a laboratory-scale crusher and sieved to ensure uniform size. Later, it was stored at 4°C until used. In the current study, the inoculum was composed of acclimatized digested manure (ADM), acclimatized sludge (AS), and mixed inoculum (MI) (50% ADM + 50% AS). ADM was collected from a local biogas plant that is feeding cow manure from Hyderabad, Sindh, and AS was collected from a lab-scale continuous digester treating the activated sludge. Laterite was collected from a local mining company located in the Sindh province of Pakistan.

2.2 Experimental Setup and Conditions

A biochemical methane potential (BMP) laboratory-scale experiment was conducted for CS following the methodology proposed by Chynoweth, et al. [19], with slight modifications. In this present study, 300 mL glass serum bottles were used as BMP reactors with 75% (225 mL) working volume. Thus leaving 25% headspace for biogas generation. For the BMP of CS, known quantities of CS (VS basis), inoculums (ADM, AS, and MI), and different dosages of laterite powder were introduced into the AD reactors. The bottles were tightly sealed with rubber septa with aluminum crimp caps.

For ensuring the anaerobic conditions within the batch reactor, each reactor was purged with pure nitrogen (N_2) gas for 2 minutes. As illustrated in Figure 1, the reactors were placed in a temperature-controlled water bath and operated under mesophilic conditions (37°C) for 45 days. The reactors were manually mixed three times daily; however, mixing once or more per day is generally sufficient for BMP experiments [20]. In addition, no external nutrients were supplemented within the batch BMP reactors, as all required nutrients were supplied by the fresh inoculum, i.e., ADM, AS, and MI [21] and laterite powder. This study comprises two laboratory-scale experiments. In the first experiment, three different inocula (ADM, AS, and MI) were assessed on the AD of CS. In the second laboratory-scale experiment, the best inoculum was selected from experiment 1, and six sets of reactors were prepared, viz., ADM+0% LP, ADM+2% LP, ADM+4% LP, ADM+6% LP, ADM+8% LP, and ADM+10% LP.



1. Water Bath 2. Thermocouple 3. Immersion Heater 4. Temperature Controller
5. Multi foil biogas collection bag

Fig. 1. Experimental setup for anaerobic digestion

2.3 Analytical Parameters

For characterization of biomass and inoculum, fresh samples of the CS and all three inoculums (ADM, AS, and MI) were analyzed for pH, total solids (TS), VFA, volatile solids (VS), and total alkalinity. Furthermore, the total organic carbon (TOC) and total Kjeldahl nitrogen (TKN) of both the substrate and inoculums were determined. The pH of CS was analysed using 1:5 suspension of water to biomass sample. Also, the daily biogas production was measured using a specific glass syringe designed for gas volume measurement. The total organic carbon (TOC) of CS and inoculums (ADM, AS, and MI) was calculated using Eq. (1) as reported in previous study [22]. Nevertheless, the parameters TKN, VFAs, TS, VS, pH, and alkalinity of digester samples were determined according to the conventional techniques recommended in the literature [23]. The VS elimination percentage was calculated using Eq. 2 after 45 days of anaerobic digestion.

$$\mathrm{TOC} = \mathrm{VS}\ (\%\ \mathrm{of\ TS})/1.724 \rightarrow (1)$$

$$\mathrm{VS\ removal}\ (\%) = \left(\frac{\mathrm{VS\ (added)} - \mathrm{VS(Final)}}{\mathrm{VS(added)}}\right) * 100 \rightarrow (2)$$

SEM-EDS Zeiss Sigma 500 VP used for elemental mapping of laterite particles. Whereas the Olympus Vanta X-ray Fluorescence (XRF) was used to quantitative elemental analysis. The specific surface area of laterite was obtained by applying the Brunauer-Emmet-Teller (BET) method to N_2 isotherms measured at -196 °C.

2.4 Statistical and Kinetics analysis

For BMP batch experiments and analysis of both the experiments were performed in triplicate. The average values were reported in the graphs and tables. The statistically significant differences ($p < 0.05$) between various conditions assessed in both experiments were interpreted using ANOVA. .

Averaged biogas generation values obtained from both experiments were used for biokinetic model fitting. Therefore, non-linear biokinetic model fitting was performed to understand and simulate the cumulative biogas yield by using MGM [24] as shown in Eq. (3).

$$\mathrm{M} = \mathrm{P_b} \times \exp\left\{-\exp\left[\frac{\mathrm{R_m} \cdot \mathrm{e}}{\mathrm{P_b}}(\lambda - \mathrm{t}) + 1\right]\right\} \rightarrow (3)$$

3. Results and Discussion

3.1 Feedstock characteristics

The feedstock characteristics of waste agricultural biomass play a crucial role in the management, operation, and design of anaerobic reactors. These initial properties of CS strongly influence reactor startup, process stability, and biogas production during AD. The initial pH of CS was measured at 5.9, while anaerobically digested manure (ADM), activated carbon (AC), and microbial inoculum (MI) showed initial pH values of 6.9, 6.7, and 6.8, respectively. Furthermore, CS showed a notably high volatile solids content of 92.16% TS. Initial characteristics of CS, ADM, and AC are reported in Table 1. CS has high carbon and low nitrogen content, as shown in Table 1, whereas the C/N ratios of the studied inocula (ADM, AS, and MI) were in the range of 10.40–12.68, as presented in Table 1. In addition, high TKN content of inoculum might balance the TOC/TKN ratios during AD of CS. The initial characteristics of CS and ADM are similar and comparable to the results of another study [4].

Table 1

Main characteristics of different inocula and canola straw

Parameters	Digested manure	Acclimatized Sludge	Mixed Inoculum	Canola Straw
Ph	6.9±0.2	6.7±0.1	6.8±0.2	5.9±0.1
TS (%)	5.90±0.22	5.71±0.34	5.88±0.28	92.16±0.28
VS[1]	71.92±0.37	69.92±0.28	70.22±0.39	84.08±1.11
MC (%)	94.10±0.22	90.10±0.11	93.10±0.15	7.4±0.28
TKN[1]	3.67±0.43	2.99±0.51	3.37±0.13	0.97±0.11
TOC[1]	38.26±0.34	37.92±0.76	37.99±0.15	54.71±0.64
Cellulose (%)	-	-	-	34.9±0.25
Hemicellulose (%)	-	-	-	24.1±0.35
Lignin (%)	-	-	-	19.4±0.45
C/N ratio	10.40	12.68	11.27	56.40

[1](% of TS)

3.2 Physiochemical and mineralogical characteristics of laterite

The Jhimpir laterite used in this study was characterized to determine its physical, chemical, and surface properties, which were used in AD of CS. Nonetheless, PSD analysis revealed that around 80% of the laterite sample passed below 100 µm, with significant mineral liberation occurring below 600 µm, as shown in Figure 2. As fine particle size favors higher surface reactivity and better interaction with the microbial population in the digester during AD. Elemental analysis (Table 2) revealed that the laterite powder predominantly contained Fe (45.61 wt.%), along with substantial Si (1.86 wt.%), Al (2.142 wt.%), Ca (2.584 wt.%) and minor concentrations of Mg, S, and Ti components, as presented in Table 2. The relatively high iron content and low levels of toxic metals make this material suitable as a micronutrient source and redox-active additive in AD systems.

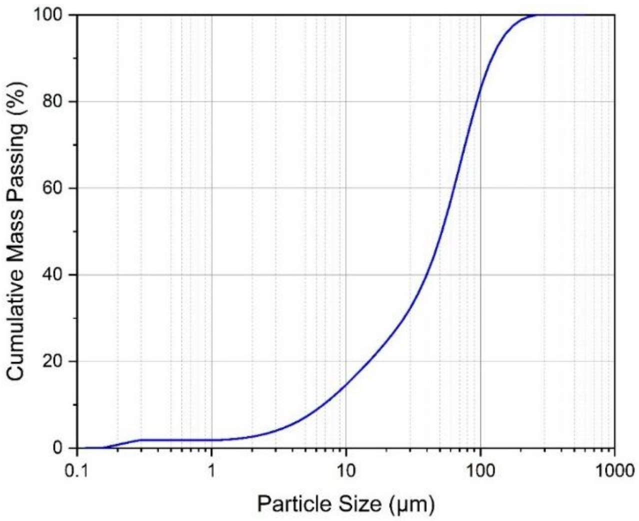


Fig. 2. Particle size distribution of laterite powder

Table 2

Elemental analysis of laterite powder

Sr#	Elements	%
1	Fe	45.61
2	Ca	2.584
3	Al	2.142
4	Si	1.865
5	Mg	1.67
6	S	1.436
7	Ti	0.246
8	Mn	0.093
9	LE	Remaining

In Figure 3, SEM analysis of laterite powder further revealed an irregular porous morphology with micro-cavities and rough surfaces. Furthermore, a large surface area is conducive to the attachment of microbes which can be observed in Figure 3.

The BET surface area (11.8 m²/g) supports this high reactivity. The EDS spectra demonstrated the dominance of Fe and O, confirming the presence of Fe oxides, while Si and Al were distributed in localized regions as quartz and aluminosilicate impurities. Moreover, similar findings were also reported on the structural and mineralogical features of laterite [25] which is in line with the findings of the present study. Moreover, optical microscopy images further showed dark brown to reddish-brown grains, typical of hematite and goethite, interspersed with lighter, translucent quartz particles. These textural features indicate that the laterite contains conductive iron oxides embedded in a siliceous matrix, capable of acting as both an electron mediator and microbial support surface during AD of CS.

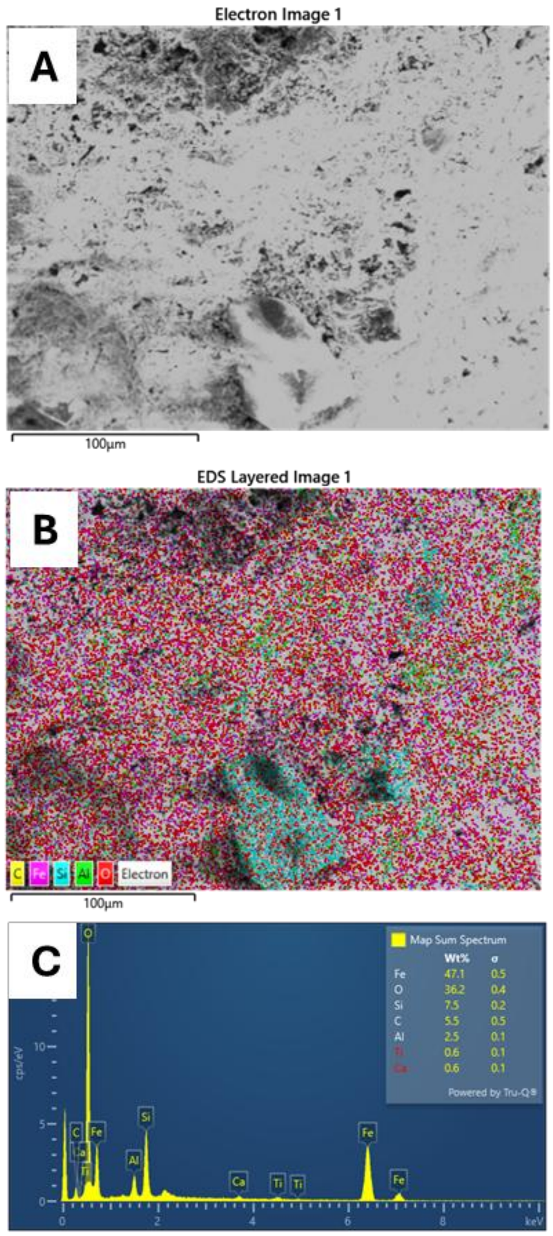


Fig. 3. *SEM and EDS analysis of laterite powder*

3.3 Effect of Inoculum source and laterite powder on buffer capacity and reactors stability

Initial and final pH of all the reactors inoculated with ADM and AS were measured as depicted in Table 3. Methanogenesis requires an optimal pH range between 6.5 and 8.2, as reported in the literature [26], and exceeding a pH value of 8.5 can have toxic effects on the anaerobic digestion (AD) of biomass [27]. However, initial pH in all the reactors ranged between 7.2 and 7.5; all the values were in a desirable range for successful commencement of AD. Additionally, the final pH values of all reactors inoculated with ADM, AS, and MI, as well as the reactor that received various concentrations of laterite powder, were within a favorable range, as shown in Table 3. However, reactors in which laterite powder was added showed a neutral final pH range. In AD, total alkalinity is another appropriate parameter used to identify reactor imbalances after pH.

Table 3

Stability parameters of anaerobic digestion reactors

Conditions	pH	pH	VFA (mg/L)	VFA (mg/L)	TA (mg/L)	TA (mg/L)	VFA/TA	VFA/TA
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
ADM	7.2±0.2	6.9±0.1	398±3	938±5	999±4	2490±7	0.39	0.4
AS	7.4±0.1	6.2±0.3	331±6	782±8	926±4	1990±2	0.35	0.39
MI	7.4±0.2	6.8±0.1	378±3	799±4	1040±5	2043±2	0.36	0.39
ADM+0% LP	7.2±0.2	6.9±0.2	399±2	932±4	992±2	2470±3	0.40	0.37
ADM+2% LP	7.2±0.4	7.0±0.2	278±3	732±4	899±2	2189±6	0.30	0.33
ADM+4% LP	7.3±0.3	7.2±0.2	222±5	622±2	912±8	2252±2	0.24	0.27
ADM+6% LP	7.5±0.2	7.2±0.2	211±2	601±4	912±9	2282±2	0.23	0.26
ADM+8% LP	7.4±0.2	7.3±0.2	213±3	600±2	928±4	2310±2	0.22	0.25
ADM+10% LP	7.5±0.2	7.3±0.1	209±3	598±8	989±6	2489±2	0.21	0.24

In this work, the only sources of total alkalinity were ADM, AS, and MI. Therefore, no additional alkalinity was provided in any of the AD experiments. Table 3 presents the initial and final total alkalinity values of the anaerobic reactors. Reactors inoculated with ADM exhibited higher initial and final alkalinity during the anaerobic digestion (AD) of canola straw (CS). This elevated alkalinity contributed to enhanced biogas production in ADM-inoculated reactors compared to those inoculated with AS and MI. As shown in Table 3, the initial and final volatile fatty acid (VFA) concentrations in all reactors remained within the optimal range for AD. According to the literature, VFA concentrations exceeding 5000 mg/L can further stimulate the anaerobic digestion process [28]. Most of the studies have assessed and reported the digester stability as VFA/alkalinity ratios [6, 29]. All the batch reactors inoculated with ADM, AS, and MI and the addition of different concentrations of laterite powder showed a desirable range of VFA/alkalinity ratios, as shown in Table 3. According to a study by Kafle and Kim [30], the VFA/TA ratio should be less than 0.4 for improved methanogenesis performance. However, it may be noted that reactors with the addition of laterite powder smoothly produce the VFAs with sufficient alkalinity as compared to reactors in which no laterite powder was added. Therefore, it may be concluded that a digester inoculated with ADM with the addition of laterite powder shows better buffering capacity and reactor stability based on VFA/TA ratios as shown in Table 3.

3.4 Effect of Inoculum source on the biogas production of Canola Straw

In this study three different inoculum sources, such as ADM, AC, and MI, were compared on the AD of CS, as shown in Figure 4. The biogas generation yield from the AD of CS inoculated with ADM, AC, and MI was reported in Figure 4. During the starting days of digestion, ADM provides a higher biogas yield from CS as compared to other inoculums. The reactor inoculated with ADM showed a noticeable trend in biogas generation after 9 days of anaerobic digestion. Nonetheless, the highest yield of daily biogas was 23.39 NmL/gVS, which was observed after 23 d of digestion from CS inoculated with ADM, as shown in Figure 4A. However, the lowest biogas yield, in comparison with ADM, was observed in the reactor inoculated with AS and MI. Thus, reactors inoculated with ADM were more efficient than those inoculated with other types, as they exhibited steadier and smoother production. Moreover, the highest daily biogas yields from AS and MI inoculated reactors were observed after 20 and 16 d of AD.

The cumulative biogas yields of CS in reactors inoculated with ADM, AS, and MI were 427, 362, and 383 NmL/gVS, respectively. The highest cumulative biogas yield of 427 NmL/gVS was achieved in the reactor inoculated with ADM, whereas the lowest biogas yield was obtained from the reactor inoculated with AS, as illustrated in Figure 4B. Based on the results of the present study in Figure 4, it may be clearly concluded that significant ($p < 0.05$) differences existed between ADM, AS, and MI when used as an inoculum in the AD of CS. However, biogas production from CS inoculated with ADM was 15.23% and 10.31% higher than from AS and MI. A more stable and higher biogas production was observed in the anaerobic reactors inoculated with ADM. Overall, all inocula showed satisfactory performance during the anaerobic digestion of CS, as shown in Figure 4.

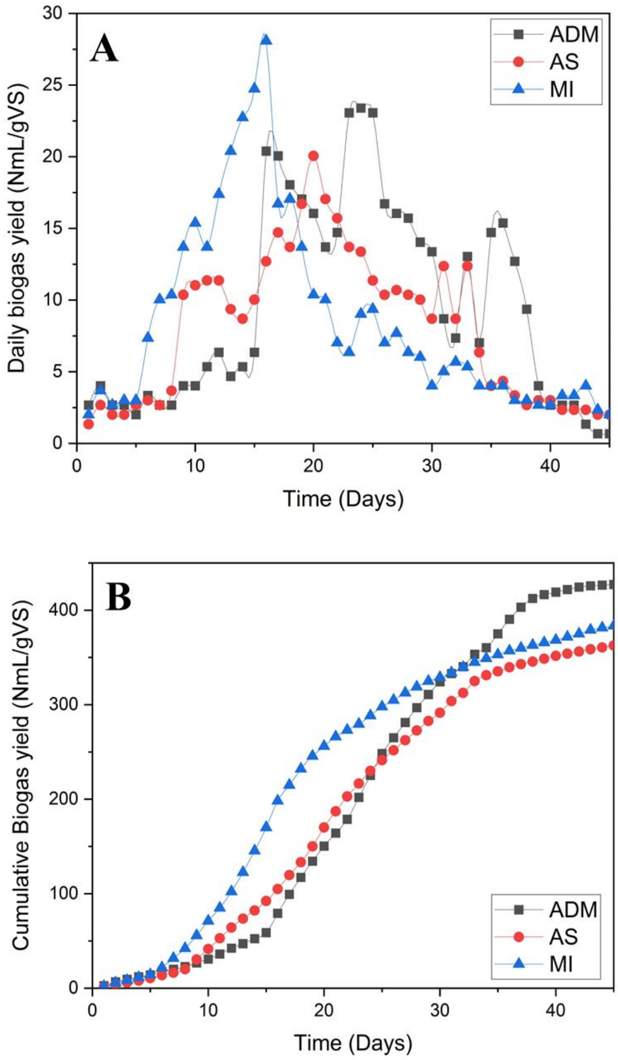


Fig. 4. Effect of different inoculum source on the (A) daily biogas production (B) cumulative biogas production of canola straw.

The findings of the present study on different inoculum sources are consistent with those reported by Gu et al., [16], who compared various inocula for the AD of rice straw. Digested manure showed better performance in terms of nutrient balance, buffering capacity, and biogas production. The higher biogas yield may be attributed to the greater microbial population present in the manure-based inoculum [31]. Similarly Rajput & Sheikh [6] evaluated three inoculum types, i.e., digested manure, septic tank sludge, and acclimatized sludge, for the AD of sunflower meal and wheat straw. Reactors inoculated with digested manure performed better than those with other inocula. These results are in satisfactory agreement with the findings of the present study. Moreover, inoculum pretreatment such as sieving and pre-incubation in anaerobic conditions further enhance the efficiency of inoculum and ultimately effect the AD of biomass [32, 33].

3.5. Effect of Inoculum Source and Laterite Powder Addition on the Anaerobic Digestion of Canola Straw

Figure 5 presents the effect of various laterite concentrations (2, 4, 6, 8, and 10%) with inoculum ADM on the cumulative biogas generation of CS. Rapid daily biogas yield was observed from reactors in which 2 and 4% of laterite powder was added, as shown in Figure 5A. The biogas yields significantly increased ($p < 0.05$) in the reactors that had laterite powder added compared to the raw reactors. However, the highest cumulative biogas was observed for the reactor fed with ADM+2% LP, which was 602 NmL/gVS, while for ADM+0% LP, ADM+4% LP, ADM+6% LP, ADM+8% LP, and ADM+10% LP, the yield was 402, 575, 561, 486, and 417 NmL/gVS, respectively. As the concentration of laterite powder was increased from 2%, the biogas production was reduced, as shown in Figure 5. Therefore, a low concentration of laterite powder was feasible to enhance the biogas production from CS.

Reduction in biogas production was observed as the laterite concentration was increased might be attributed to excessive conductivity as high ionic strength disturb the microbial population during AD [34]. Moreover, surface passivation might be another reason due to saturation of adsorbent surface which reduces the efficiency of iron rich materials during AD [35]. Presence of high amount of trace elements in laterite powder may further reduce the efficacy of AD process which might be another reason for low biogas production as the laterite powder dosages was increased from 2% [34].

The results of the present study indicated that the lower concentration of laterite powder addition (2%) had a more positive outcome as compared to the higher concentration of laterite powder addition. The methane content of reactors ADM+0% LP, ADM+2% LP, ADM+4% LP, ADM+6% LP, ADM+8% LP, and ADM+10% LP addition was 58.12%, 66.17%, 60.17%, 59.88%, 59.89%, and 59.74%, respectively. The addition of 2% laterite powder to the AD of CS showed higher methane content compared to the

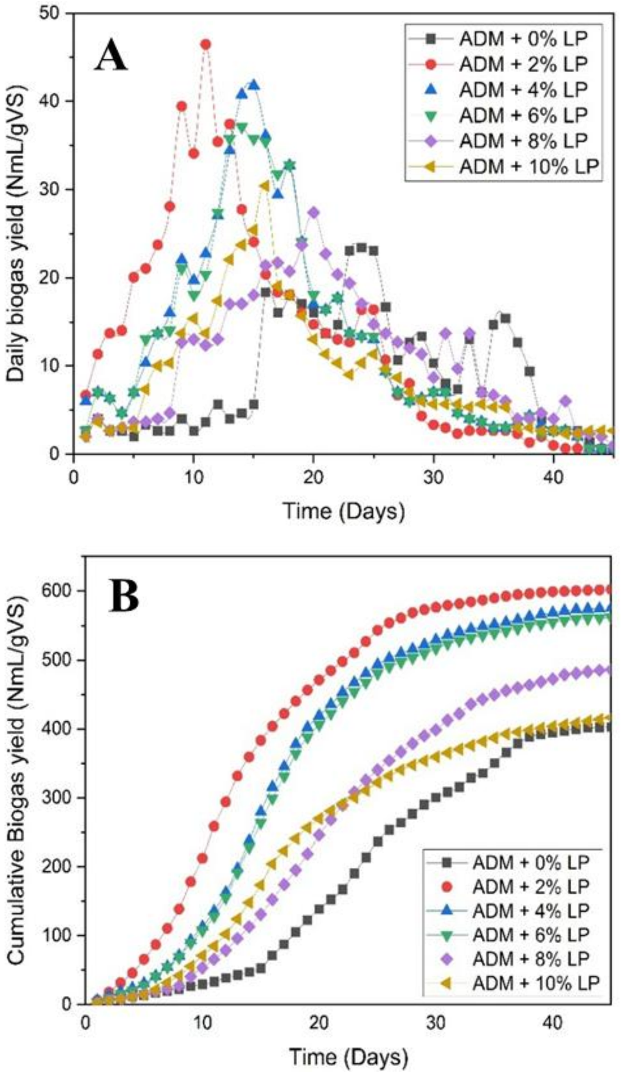


Fig. 5. Biogas production (A) daily (B) cumulative of canola straw inoculated with anaerobically digested manure at different concentrations of laterite powder

reactor in which higher and no laterite powder was added. Increase in biogas production up to 1.6-fold from waste activated sludge supplemented with iron source was also reported in the previous literature [36]. Another study in the literature positively correlated iron source addition and enhancement in biogas production [37]. Furthermore, addition of trace elements supplementation also enhanced the biogas recovery and prevent the inhibition during AD [38]. All these reported findings are in line with results of the present study, due to DIET mechanism as shown in Figure 6.

The physicochemical attributes of laterite powder might play a critical role in enhancing the performance of AD of CS when used as a mineral additive. The abundance of Fe-oxides such as hematite and goethite [25] contributes to DIET, thereby improving the efficiency of methanogenic pathways during the AD of CS.

Tariq et al. [18] used laterite powder up to 0.3% on the AD of cow manure and found that biogas yield was significantly increased with the higher removal of chemical oxygen demand, thus achieving results comparable to those of biochar. This enhancement in CH_4 yield was attributed to the redox-active and conducive nature of laterite powder during AD which facilitates the electron flow between methanogenesis and syntrophic bacteria [39].

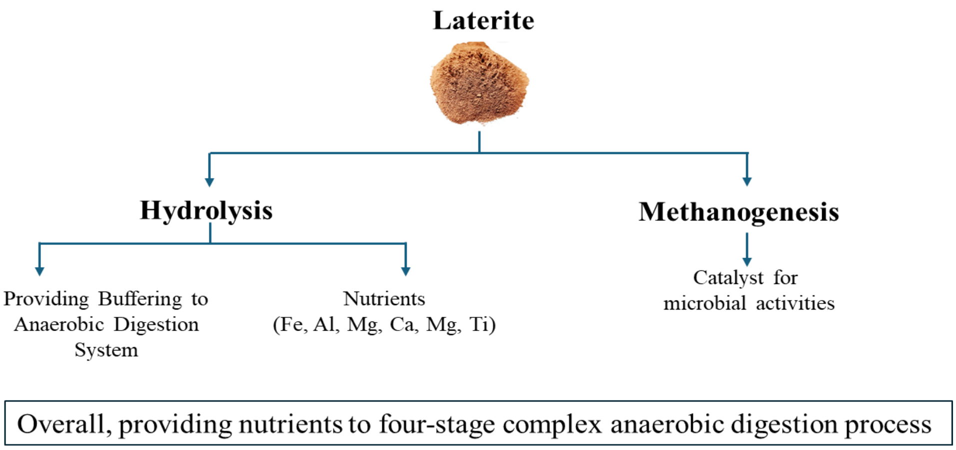


Fig. 6. *DIET Mechanism*

3.6. Role of inoculum source and laterite powder on VS reduction.

VS reduction in AD system performs as a key indicator for the assessment of the overall performance and stability of the AD process. In Figure 7, VS reduction from different reactors inoculated with ADM, AS, and MI during the first phase of AD experiment was presented. However, the reactors inoculated with ADM achieved the maximum VS reduction of 66% and similar trends like biogas yield were observed, whereas the reactor inoculated with AS showed the low reduction of 52% from CS in comparison with ADM as shown in Figure 7. The trend in VS reduction closely followed that of biogas generation, indicating that higher VS degradation corresponded to increased biogas yield, as demonstrated in Figures 4, 5 and 7. The reactor containing CS and inoculated with ADM exhibited the most significant VS removal. Furthermore, a strong positive correlation was observed between VS reduction and biogas yield, which was associated with improved buffering capacity and volatile fatty acid (VFA) production. Similar findings have been reported in previous studies, where enhanced solids degradation was directly linked to elevated biogas output during the anaerobic digestion of rice straw [40].

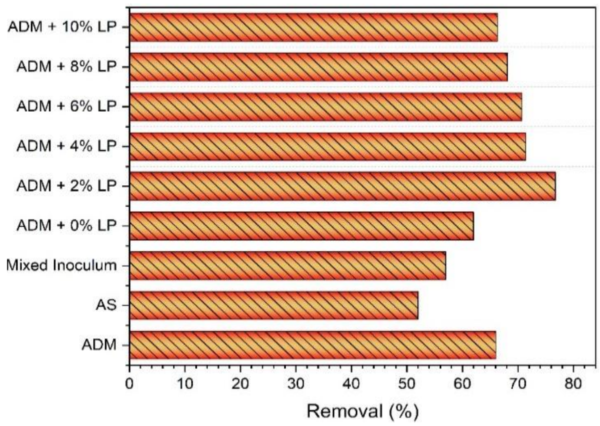


Fig. 7. *Volatile solids removal from reactors with different inoculum sources and laterite powder addition*

In the second part of the study, illustrated in Figure 6, the reactors with 2% laterite powder achieved the highest VS reduction of 76.74%, while the reactor without any laterite powder had the lowest VS reduction at only 62%. In addition, the reactors in which 4, 6, 8, and 10% laterite powder were added have VS reductions of 71.41, 70.72, 68.1, and 66.32%, respectively. As compared to the reactor in which only CS was added, the VS reduction for 2% added laterite powder was increased by 20%. The results of VS reduction are in good correlation with the results of biogas production, as shown in Figures 4 and 5. As the biogas production was increased, the VS removal was increased from the reactors. The ADM-inoculated reactor performed better; the 2% addition of laterite powder gave the highest VS reduction and showed the highest biogas yield.

3.7. Kinetic Study

The results of the kinetic study regarding the effect of different inoculum sources and the addition of laterite powder on biogas production utilizing MGM are presented in Table 4. Various studies have reported the biokinetic parameters of AD utilizing MGM in the literature [41, 42]. Nonetheless, in the first part of the present study, the R^2 values of the different inoculum sources ranged from 0.997 to 0.999. Furthermore, the biogas production values estimated by the MGM for the reactors inoculated with ADM were significantly higher than those for AS and MI. Moreover, it is noteworthy that the reactor inoculated with MI showed a short lag phase duration (5.12 days) in comparison to ADM and AS, as shown in Table 4. This may be due to the mixing of the inocula. In the second part of the present study, R^2 values for various dosages of laterite powder added to CS were between 0.996 and 0.999. Table 4 indicates that the reactor (ADM+2% LP) exhibits the maximum biogas production potential (Pb) and a shorter lag phase duration of 3.84 days, as calculated by the MGM provided in Table 4. Overall, successful fitting of biokinetic MGM was performed, and biogas yield data was reproduced.

Table 4

Biokinetics parameters of MGM for different inoculum sources and laterite powder on the anaerobic of Canola straw

Conditions	[1]P_b (NmL/gVS)	[2]λ (d)	R^2
ADM	422.2	8.23	0.999
AS	351.1	8.44	0.997
MI	371	5.12	0.997
ADM+0% LP	399.8	10.21	0.999
ADM+2% LP	596.98	3.84	0.999
ADM+4% LP	572	9.1	0.999
ADM+6% LP	559.3	9.20	0.997
ADM+8% LP	485.14	9.2	0.999
ADM+10% LP	414.7	10.12	0.996

[1]P_b = Biogas production potential, [2]λ= lag phase time

4. Conclusion

The study demonstrated that the performance of anaerobic reactors varied significantly with different inoculum sources, influencing biogas yield, buffering capacity, and volatile solids (VS) reduction. Reactors inoculated with ADM have shorter start-up time as compared to other inoculum. Addition of 2% laterite powder during AD of CS showed higher biogas production and VS removal due to DIET and better availability of nutrients. Additionally, when assessing the economic viability, it is important to consider the value of by-products such as digestate and biomethane, since the addition of laterite powder will improve the nutrient content in the digester. By considering all these factors, addition of laterite powder at low concentrations followed by its AD could be a sustainable approach to enhance biogas generation and improve the quality of digestate from CS. Moreover, laterite is indigenous rock and locally available and may be used to enhance the AD of biomass. The addition mechanism for laterite powder may be added at the biogas plant. Furthermore, only 2% addition of laterite powder significantly enhanced the biogas production which will positively contribute in terms of overall cost of the system.

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