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Performance Evaluation of Banana Fiber as a Natural Adsorbent for Methane Enhancement in Biogas Using GC–MS Analysis

I Wayan Sutama [1)*], I Nyoman Suprapta Winaya [2)], Ida Bagus Alit Swarmardika [3)], Rukmi Sari Hartati [4)], I Made Panji Tirta Prakasa [4)]

1) Program Of Doctor Engineering Science Universitas Udayana, Indonesia
2) Mechanical Engineering Study Program Universitas Udayana, Indonesia
3) Electrical Engineering Study Program Universitas Udayana, Indonesia
4) Electrical Engineering Study Program Universitas Pendidikan Nasional, Indonesia

Corresponding email 1)* : wayansutama@undiknas.ac.id

Abstract. Biogas utilization from agricultural waste in Indonesia remains underdeveloped despite its significant potential as a renewable energy source. Biogas produced through anaerobic digestion contains a high concentration of carbon dioxide (CO_2), which lowers its calorific value and limits its direct use as a clean fuel. Therefore, biogas upgrading is necessary to increase methane (CH_4) concentration and improve fuel quality. This study evaluates the performance of banana fiber as a natural adsorbent for methane enhancement and carbon dioxide removal in biogas. Banana fiber was selected because of its lignocellulosic composition and porous structure, which provide potential adsorption sites for gas molecules. The experimental setup employed a fixed-bed filtration system in which raw biogas from an anaerobic digester was passed through a column packed with untreated banana fiber. Gas samples were collected before and after filtration and analyzed using Gas Chromatography–Mass Spectrometry (GC–MS) to determine changes in CH_4 and CO_2 concentrations. The results showed that methane concentration increased from 51.37% to 60.84%, corresponding to an enhancement of 9.47%, while carbon dioxide concentration decreased from 48.63% to 39.15%, representing a reduction of 9.48%. These findings indicate that banana fiber effectively improves biogas quality by selectively adsorbing CO_2 and enriching methane content. The adsorption performance is attributed to the presence of hydroxyl (–OH) and carboxyl (–COOH) functional groups in the lignocellulosic structure of banana fiber, which facilitate physical adsorption and enhance gas–solid interactions. In addition, the porous structure of the fiber increases surface area and supports adsorption efficiency. This study demonstrates the effectiveness of untreated banana fiber as a low-cost and environmentally friendly adsorbent for biogas upgrading using GC–MS analysis. The findings highlight its potential application in small-scale and decentralized renewable energy systems, particularly in rural and agricultural areas. Furthermore, the study provides important implications for laboratory-scale biogas purification systems and future industrial biogas upgrading applications.

Keywords : Biogas, Banana Fiber, Methane Enhancement, CO_2 Removal, Natural Adsorbent

1. INTRODUCTION

The increasing global demand for sustainable and environmentally friendly energy sources has become a critical issue due to climate change, environmental degradation, and the depletion of fossil fuel reserves. The continued dependence on fossil fuels has significantly contributed to greenhouse gas emissions, which are the main drivers of global warming and environmental instability. Therefore, the development of renewable energy technologies has become an essential strategy to achieve energy sustainability and reduce environmental impact [1], [18]. Among various renewable energy sources, biogas has emerged as a promising alternative due to its ability to convert organic waste into usable energy. Biogas is produced through the anaerobic digestion of organic materials such as agricultural residues, livestock manure, and food waste. Anaerobic digestion has been widely studied for organic waste treatment [14]. This process not only generates energy but also contributes to waste management and environmental protection, making it an important component in circular economy systems [17], [18].

However, raw biogas contains a significant amount of carbon dioxide (CO_2), which reduces its calorific value and limits its direct application as a clean fuel. The presence of CO_2 leads to lower combustion efficiency, unstable flame characteristics, and reduced energy output. Therefore, biogas upgrading is required to increase methane (CH_4) concentration and improve overall fuel quality [2], [3]. Various technologies have been developed for biogas upgrading, including water scrubbing, chemical absorption, membrane separation, and pressure swing adsorption. Although these methods are effective, they generally require high capital investment, complex operational systems, and considerable energy consumption [4]. These limitations make conventional upgrading technologies less suitable for small-scale and decentralized applications, particularly in rural areas.

To address these challenges, recent studies have focused on the use of low-cost and environmentally friendly adsorbents derived from biomass. Natural fibers have gained considerable attention due to their abundance, biodegradability, and renewable characteristics. Lignocellulosic materials such as rice husk, coconut fiber, and agricultural residues have demonstrated potential for gas adsorption due to their porous structure and the presence of functional groups that facilitate gas interaction [5], [6]. Banana fiber is one of the most abundant agricultural wastes in tropical regions and is often underutilized. It consists primarily of cellulose, hemicellulose, and lignin, which provide a fibrous and porous structure suitable for adsorption processes. The presence of polar functional groups such as hydroxyl (–OH) and carboxyl (–COOH) enables banana fiber to interact with gas molecules, particularly carbon dioxide, through physical adsorption mechanisms such as hydrogen bonding and van der Waals interactions [6]. From a sustainability perspective, the utilization of banana fiber aligns with the concept of circular economy, where agricultural waste is transformed into value-added materials for energy applications. This approach not only reduces environmental pollution but also enhances resource efficiency and supports sustainable energy production, especially in developing regions. Previous studies have shown that natural fibers can improve biogas quality by reducing carbon dioxide and increasing methane concentration.

Previous studies have also confirmed that lignocellulosic materials contain active functional groups that contribute significantly to adsorption processes [5], [7]. However, the adsorption performance of natural fibers varies depending on their chemical composition, surface characteristics, and structural properties. Despite the growing interest in biomass-based adsorbents, studies specifically investigating untreated banana fiber as a direct adsorbent for biogas upgrading remain very limited. Most previous studies have focused on activated carbon, chemically modified biomass, or synthetic adsorbent materials [18], [19], which often require additional chemical treatment, higher production costs, and more complex preparation processes. In contrast, untreated banana fiber offers advantages in terms of availability, low cost, biodegradability, and environmental sustainability, making it highly suitable for decentralized and small-scale renewable energy systems. In addition, previous studies have generally concentrated only on changes in biogas composition without providing detailed analysis of the adsorption mechanism occurring within the adsorbent material. Limited studies have integrated gas composition analysis with material characterization techniques to explain the interaction between biomass fibers and gas molecules during the adsorption process. Therefore, a comprehensive understanding of both adsorption performance and molecular interaction mechanisms remains insufficient [20].

This study is distinct because it combines Gas Chromatography–Mass Spectrometry (GC–MS) analysis and Fourier Transform Infrared (FTIR) characterization to evaluate both methane enhancement performance and adsorption mechanisms in untreated banana fiber. Furthermore, the implementation of a fixed-bed upflow adsorption configuration provides a simple, low-cost, and practical purification system suitable for laboratory-scale and rural biogas upgrading applications. The novelty of this research lies not only in the use of untreated banana fiber as a sustainable adsorbent material, but also in the integration of performance evaluation and functional group characterization to explain the adsorption behavior of carbon dioxide in a biogas purification system. Therefore, this study aims to evaluate the effectiveness of banana fiber as a natural adsorbent for methane enhancement through carbon dioxide removal using GC–MS analysis, supported by FTIR characterization to explain the adsorption mechanism in a fixed-bed filtration system. This research is expected to contribute to the development of environmentally friendly and economically feasible biogas upgrading technologies for small-scale renewable energy applications [21]. In addition to conventional upgrading technologies, several studies have explored the use of packing materials and biofiltration systems for biogas purification. These approaches utilize natural or engineered media to enhance gas–solid interaction and improve removal efficiency of unwanted gases such as carbon dioxide and hydrogen sulfide [10], [11], [12]. Furthermore, hydrogen sulfide removal using bio-based adsorbents has also been widely investigated due to its corrosive nature and environmental impact [9].

2. METHODS

2.1 Materials

The materials used in this study consisted of banana fiber as a natural adsorbent and raw biogas obtained from an anaerobic digester. Banana fiber was selected due to its lignocellulosic composition, which includes cellulose, hemicellulose, and lignin that provide potential adsorption sites for gas molecules [5], [6]. The biogas used in this study was generated from the anaerobic digestion of organic waste and collected directly from the digester outlet. Biogas generally consists of methane (CH_4) and carbon dioxide (CO_2) as the main components, which determine its energy quality [2], [3]. Therefore, these two parameters were used as the main indicators in evaluating the performance of the adsorption process.

2.2 Experimental Setup

The experimental system was designed using a fixed-bed adsorption method to evaluate the performance of banana fiber in improving biogas quality. Fixed-bed systems are widely used in gas purification due to their simplicity, low cost, and effectiveness in adsorption processes [4]. Previous studies have demonstrated that the effectiveness of fixed-bed systems is influenced by parameters such as packing material characteristics, gas residence time, and flow configuration, which directly affect adsorption performance [10], [12].

2.2.1 Operational Parameters

Several operational parameters were controlled during the experimental process to ensure stable adsorption performance and reproducibility of the system. The fixed-bed adsorption column was constructed using a PVC tube with an inner diameter of 7.5 cm and a total height of 50 cm. The adsorption column was packed with approximately 250 g of untreated banana fiber using a loose packing configuration to maintain porosity and minimize pressure drop during gas flow.

The raw biogas flow rate was maintained at approximately 2 L/min using a manual flow control valve. The filtration process was conducted under atmospheric pressure conditions with an estimated gas residence time of approximately 45–60 seconds inside the adsorption column. The upflow configuration was selected to improve gas distribution and maximize gas–solid interaction between biogas and the banana fiber adsorbent.

The experiments were performed at ambient laboratory temperature ranging from 28–30°C. Gas samples were collected before filtration (inlet) and after filtration (outlet) using gas sampling bags for subsequent GC–MS analysis. All experiments were conducted in triplicate to ensure data reliability and reproducibility.

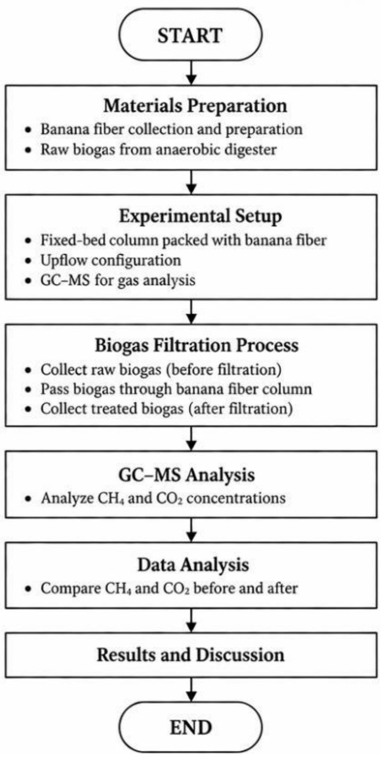

Figure 1. Research flowchart of biogas upgrading using banana fiber

Figure 1 illustrates the overall research workflow used in this study. The process begins with banana fiber preparation and raw biogas collection, followed by the adsorption filtration process using a fixed-bed system. The workflow also includes GC–MS analysis for gas composition evaluation and FTIR characterization to investigate the adsorption mechanism occurring in the banana fiber after filtration. The research procedure consisted of several stages, including banana fiber preparation, experimental setup, raw biogas collection, flow regulation, filtration process, gas sampling, GC–MS analysis, FTIR characterization, and data interpretation.

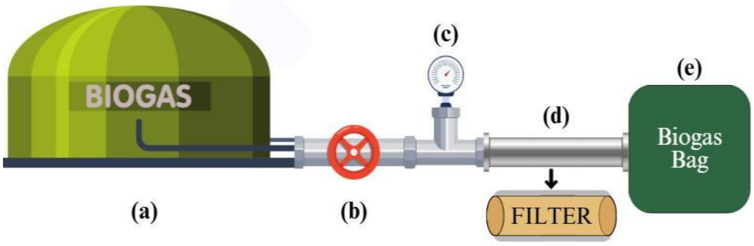

Figure 2. Schematic diagram of the experimental setup: (a) raw biogas source, (b) flow control valve, (c) monitoring gauge, (d) banana fiber filter column, and (e) biogas sampling bag

Figure 2 presents the schematic configuration of the fixed-bed biogas filtration system used in this study. The upflow system configuration was designed to improve gas distribution and increase contact between the biogas and the banana fiber adsorbent. The filtration column serves as the main adsorption chamber where carbon dioxide reduction and methane enrichment occur during the purification process. The system consisted of five main components. Raw biogas (a) was collected from the anaerobic digester outlet and directed into the system. The gas flow was regulated using a control valve (b) to maintain stable operating conditions. A monitoring gauge (c) was used to observe the gas flow condition during the experiment. The biogas was then passed through a fixed-bed filtration column (d) packed with banana fiber, where the adsorption process occurred. The system was operated using an upflow configuration to enhance gas–solid interaction and ensure uniform gas distribution within the column. After filtration, the treated biogas was collected in a sampling bag (e). Gas samples were collected before filtration (inlet) and after filtration (outlet) using biogas sampling bags. The samples were subsequently analyzed using Gas Chromatography–Mass Spectrometry (GC–MS) to determine methane (CH_4) and carbon dioxide (CO_2) concentrations. GC–MS analysis was conducted to quantitatively determine methane (CH_4) and carbon dioxide (CO_2) concentrations before and after filtration. The gas samples were analyzed under standardized laboratory conditions to ensure measurement consistency and accuracy. The obtained chromatograms were interpreted based on peak area percentage to evaluate changes in gas composition resulting from the adsorption process.

Table 1. Operational parameters of the adsorption system

Parameter	Value
Column material	PVC
Column diameter	7.5 cm
Column height	50 cm
Banana fiber mass	250 g
Flow rate	2 L/min
Residence time	45–60 s
Operating temperature	28–30°C
Flow configuration	Upflow
Experimental repetition	Triplicate

2.3 Banana Fiber Preparation and Characteristics

The banana fiber used in this study was obtained from agricultural residues. The fibers were cleaned using water to remove impurities such as dust and dirt. After cleaning, the fibers were air-dried to reduce moisture content while maintaining their natural structure.

Figure 3. Raw banana fiber used as natural adsorbent before filtration process

After drying, the fibers were cut into uniform lengths to ensure consistent packing within the filtration column. The banana fibers were packed uniformly inside the adsorption column with a loose packing arrangement to maintain adequate porosity, reduce channeling effects, and facilitate uniform gas distribution during the filtration process. To further understand the adsorption mechanism, the banana fiber was characterized using Fourier Transform Infrared (FTIR) spectroscopy before and after the biogas filtration process. FTIR analysis was conducted to identify functional groups present in the banana fiber and to observe changes in chemical structure due to interaction with biogas components. FTIR characterization was performed within the wavenumber range of 4000–500 cm^{-1} to identify functional groups involved in the adsorption process. The spectra obtained before and after filtration were compared to observe changes in peak intensity and peak position associated with interaction between banana fiber and carbon dioxide molecules. The FTIR spectra were analyzed to identify key functional groups such as hydroxyl (–OH), carbonyl (C=O), C–H, and C–O groups, which are known to play an important role in adsorption processes [6], [8]. Changes in peak intensity and peak position were used as indicators of interaction between banana fiber and carbon dioxide molecules

2.4 Data Analysis

The performance of banana fiber as a natural adsorbent was evaluated by comparing methane (CH_4) and carbon dioxide (CO_2) concentrations before and after filtration. The adsorption performance evaluation was based on average values obtained from three repeated experiments. The results were expressed as mean ± standard deviation to assess the consistency and repeatability of the adsorption process. Descriptive statistical analysis was applied to compare methane enhancement and carbon dioxide reduction before and after filtration. The percentage increase in methane concentration and the percentage reduction in carbon dioxide were calculated using the following equations:

$$CH^4 \text{ increase } (\%) = \frac{CH_{4,after} - CH_{4,before}}{CH_{4,before}} \times 100 \quad (1)$$

$$CO^2 \text{ reduction } (\%) = \frac{CO_{2,before} - CO_{2,after}}{CO_{2,before}} \times 100 \quad (2)$$

These calculations were used to evaluate the effectiveness of banana fiber in improving biogas quality.

3. RESULTS AND DISCUSSION

3.1 Methane (CH_4) Enhancement

The performance of banana fiber as a natural adsorbent was evaluated based on its ability to increase methane (CH_4) concentration in biogas. The experimental results are presented in Table 2.

Table 2. GC–MS results of biogas composition before and after filtration using banana fiber

Gas Component	Before Filtration (%)	After Filtration (%)
CH_4	51.37 ± 0.72	60.84 ± 0.95
CO_2	48.63 ± 0.68	39.15 ± 0.88

The results presented in Table 2 represent the average values obtained from three repeated experiments. The relatively low standard deviation values (< ±1.5%) indicate that the adsorption process showed good repeatability and stable operational performance under the selected experimental conditions. These findings demonstrate that the fixed-bed adsorption system using banana fiber produced consistent methane enhancement and carbon dioxide reduction during repeated filtration cycles.

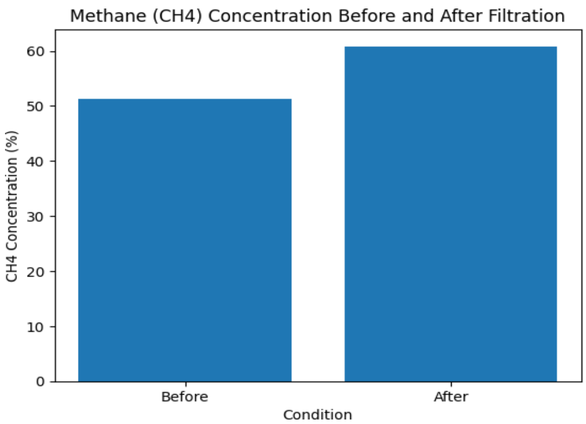

Figure 4. Methane (CH_4) concentration before and after filtration using banana fiber

Figure 4 illustrates the increase in methane concentration after the biogas filtration process using banana fiber. The increase in methane concentration indicates that the adsorption system effectively reduced non-combustible gases, particularly carbon dioxide, thereby increasing the relative methane fraction in the biogas mixture. The increase in methane concentration is not due to methane generation but rather a relative enrichment effect caused by the removal of non-combustible gases, particularly carbon dioxide (CO_2). As CO_2 concentration decreases, the volumetric fraction of methane increases proportionally, resulting in improved biogas quality [4]. The effectiveness of methane enrichment is closely related to the physical structure of banana fiber. The fibrous and porous morphology provides a large surface area, which enhances gas–solid interaction and facilitates selective adsorption of CO_2. This indirect mechanism results in increased methane concentration without altering the chemical structure of methane. Similar methane enrichment behavior has been reported in previous studies using bio-based adsorbents, where selective removal of non-combustible gases leads to an increase in methane concentration without altering its chemical composition [11], [13]. From a practical standpoint, the increase in methane concentration directly improves the calorific value of biogas, making it more suitable for applications such as cooking, heating, and electricity generation. These results indicate that banana fiber has strong potential as a low-cost material for biogas upgrading. From an engineering perspective, the methane enhancement observed in this study demonstrates the potential applicability of banana fiber for low-cost biogas upgrading systems. The increase in methane concentration contributes directly to higher calorific value and improved combustion efficiency, which are important parameters for household energy applications and small-scale electricity generation systems. The stable adsorption performance observed during repeated experiments also indicates that banana fiber can function effectively under continuous gas flow conditions.

3.2 Carbon Dioxide (CO_2) Reduction

The ability of banana fiber to reduce carbon dioxide (CO_2) concentration was also evaluated. The results show that CO_2 concentration decreased from 48.63% to 39.15%, corresponding to a reduction of 9.48% after filtration.

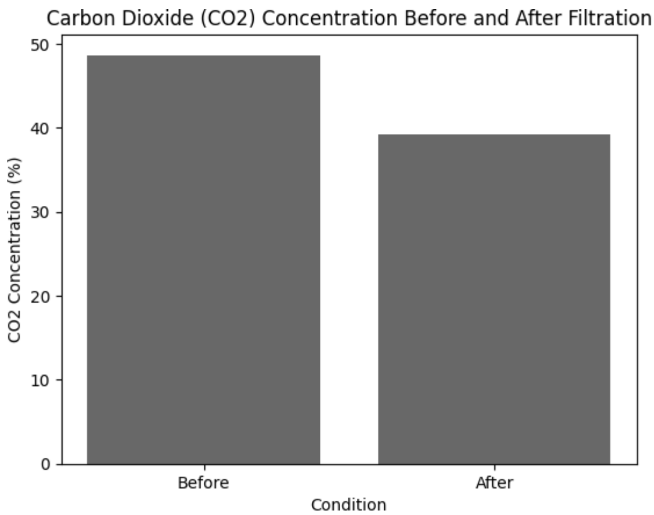

Figure 5. Carbon dioxide (CO_2) concentration before and after filtration using banana fiber

Figure 5 shows the decrease in carbon dioxide concentration after the adsorption process using banana fiber. The reduction in CO_2 concentration confirms the adsorption capability of the lignocellulosic structure of banana fiber, which provides active adsorption sites for gas molecule interaction. The reduction in CO_2 concentration can be explained through adsorption mechanisms occurring on the surface of banana fiber. This process can be described as:

$$CO2(g) + S \rightarrow CO2{\cdot}S \tag{3}$$

Where S represents the surface of the banana fiber acting as an adsorbent.

Banana fiber contains lignocellulosic components such as cellulose, hemicellulose, and lignin, which provide active sites for adsorption. Functional groups such as hydroxyl (–OH) and carboxyl (–COOH) play an important role in attracting CO_2 molecules through physical adsorption mechanisms, including hydrogen bonding and van der Waals interactions [5], [6]. In addition, the porous structure of banana fiber enhances diffusion and provides a large surface area, allowing more CO_2 molecules to be captured during the filtration process. The upflow configuration used in this study further improves gas–solid interaction and reduces channeling effects. Although the adsorption process is predominantly physical, the interaction between CO_2 and functional groups on the fiber surface contributes to the overall effectiveness of the system. The observed CO_2 reduction is consistent with previous findings on biomass-based adsorbents, where lignocellulosic materials have shown promising performance in capturing carbon dioxide due to their porous structure and functional group interactions [9], [10], [13].

3.3 FTIR Analysis of Banana Fiber

To further investigate the adsorption mechanism, Fourier Transform Infrared (FTIR) analysis was conducted to identify changes in the functional groups of banana fiber before and after the filtration process.

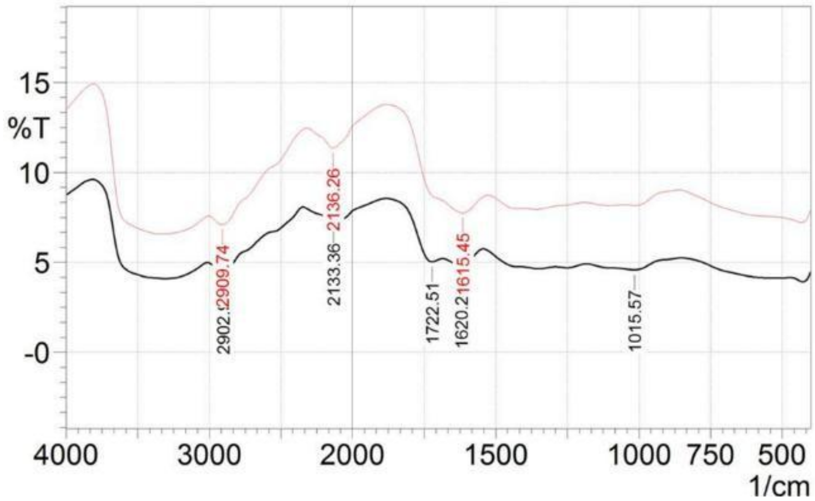

Figure 6. FTIR spectra of banana fiber before and after biogas filtration

Figure 6 presents the FTIR spectra of banana fiber before and after biogas filtration. The observed changes in peak intensity and the appearance of new absorption peaks indicate that interactions occurred between the banana fiber surface and biogas components during the adsorption process. The FTIR spectra of banana fiber before filtration show characteristic absorption bands at 3300–3500 cm^{-1} corresponding to hydroxyl (–OH) groups, 2909 cm^{-1} associated with C–H stretching, and 1615 cm^{-1} related to aromatic C=C bonds from lignin. These peaks confirm the typical lignocellulosic structure of banana fiber. After the filtration process, several changes in the FTIR spectra were observed. The intensity of the C–H stretching band decreased from 7.101 to 4.494, indicating partial degradation or interaction of cellulose components during the filtration process. In addition, new absorption peaks appeared at 1722 cm^{-1} and 1015 cm^{-1}, corresponding to carbonyl (C=O) and C–O functional groups, respectively. The emergence of these peaks suggests that chemical adsorption interactions occurred between the banana fiber and biogas components. The appearance of the carbonyl group (C=O) indicates possible oxidation or transformation of hydroxyl groups (–OH) during the adsorption process. This suggests that CO_2 molecules interact with the polar functional groups of banana fiber through surface interaction mechanisms. Furthermore, the presence of C–O stretching bands confirms the active role of cellulose in providing adsorption sites. The relatively stable aromatic C=C peak indicates that the lignin structure remains largely intact, suggesting that the fiber maintains its structural integrity during the filtration process. These FTIR results support the GC–MS findings, where CO_2 concentration decreased and methane concentration increased after filtration. Therefore, it can be concluded that banana fiber acts not only as a physical filter but also as an active adsorbent through a combination of physical adsorption and weak chemical interactions. Previous studies have also confirmed that natural fibers exhibit active functional groups that contribute significantly to adsorption processes. These functional groups play a crucial role in facilitating gas–solid interactions and enhancing adsorption efficiency [16], [17]. This result indicates that banana fiber has comparable performance to other biomass-based adsorbents reported in previous studies. Compared to previous studies using activated carbon or chemically modified biomass adsorbents, the methane enhancement achieved in this study demonstrates that untreated banana fiber can provide competitive adsorption performance while maintaining lower operational cost and simpler preparation procedures. Although the adsorption efficiency is still lower than some commercial adsorbent systems, the environmental sustainability and economic advantages of banana fiber make it highly promising for decentralized renewable energy applications.

Table 3. FTIR peak assignment of banana fiber before and after filtration

Wavenumber (cm^{-1})	Functional Group	Interpretation
3300–3500	–OH	Hydroxyl stretching vibration
2909	C–H	Cellulose stretching
1722	C=O	Carbonyl interaction after adsorption
1615	Aromatic C=C	Lignin structure
1015	C–O	Cellulose adsorption site

Although the adsorption results were promising, the adsorption capacity of banana fiber may decrease over prolonged operational periods due to saturation of active adsorption sites. Therefore, further studies are necessary to evaluate long-term adsorption performance, regeneration capability, and maximum adsorption capacity under varying operational conditions.

4. CONCLUSION

This study evaluated the performance of banana fiber as a natural adsorbent for biogas upgrading using a fixed-bed filtration system, focusing on methane (CH_4) enhancement and carbon dioxide (CO_2) reduction. The experimental results demonstrated that banana fiber effectively improved biogas quality through a simple and environmentally friendly adsorption process. GC–MS analysis showed that methane concentration increased from 51.37% to 60.84%, corresponding to an enhancement of 9.47%, while carbon dioxide concentration decreased from 48.63% to 39.15%, representing a reduction of 9.48%. These findings indicate that banana fiber can selectively adsorb carbon dioxide and contribute to methane enrichment in biogas systems. The FTIR characterization further confirmed the adsorption mechanism by revealing changes in functional groups after the filtration process. The decrease in C–H stretching intensity and the appearance of carbonyl (C=O) and C–O functional groups indicate that interactions occurred between the lignocellulosic structure of banana fiber and carbon dioxide molecules during adsorption. The results demonstrate that banana fiber functions not only as a physical filtration medium but also as an active adsorbent through surface interaction mechanisms. From a practical perspective, banana fiber offers several advantages, including low cost, wide availability, biodegradability, and environmental sustainability. The utilization of agricultural waste materials as adsorbents supports circular economy principles and provides a feasible alternative for small-scale and decentralized biogas upgrading systems, particularly in rural and developing regions. Despite the promising results, this study has several limitations. The adsorption performance was evaluated only under laboratory-scale conditions and within a relatively short operational period. The maximum adsorption capacity, saturation behavior, regeneration capability, and long-term stability of banana fiber were not investigated in this study. In addition, operational parameters such as humidity, pressure variation, packing density, and prolonged continuous gas flow may significantly influence adsorption efficiency and require further evaluation. Therefore, future studies are recommended to investigate adsorption capacity, breakthrough behavior, regeneration performance, multi-stage filtration systems, and optimization of operational parameters to improve long-term adsorption efficiency and support potential industrial-scale implementation of banana fiber-based biogas purification systems. Overall, this study demonstrates that untreated banana fiber has strong potential as a sustainable biomass-based adsorbent for low-cost biogas upgrading applications.

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