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(RESEARCH ARTICLE)

Simulation and Scale-up of Anaerobic Digestion of Cow Dung for Biogas Production Using SuperPro Designer

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Abstract

The global energy sector, heavily reliant on fossil fuels, faces significant challenges including climate change, environmental degradation, and supply constraints. This study explores biogas production from organic waste as a sustainable alternative, focusing on cow dung as a primary feedstock. The research objectives were to model an industrial-scale anaerobic digestion process, determine optimal fermentation conditions, and validate the simulation with theoretical data. A continuous stirred-tank reactor (CSTR) process was designed and simulated using SuperPro Designer software. The model incorporated key unit operations: feedstock mixing and preheating, anaerobic digestion, degasification, and biogas compression. The simulation was configured for mesophilic conditions (37°C) with a hydraulic retention time of 15 days. Results indicated a total biogas output of 1,929.88 kg/h, with a high methane purity of 73.93% (1,426.83 kg/h) following degasification. The carbon dioxide byproduct stream was separated at 503.05 kg/h (26.07%). The compressed biogas stream achieved a methane concentration of 3.70 g/L at 6.01 bar and 40°C, suitable for storage or application. The study confirms the technical viability of cow dung for renewable energy production and demonstrates the efficacy of SuperPro Designer as a tool for scaling and optimizing biogas processes, contributing to waste management and greenhouse gas reduction strategies.

Keywords: Biogas; Anaerobic Digestion; Cow Dung; Process Simulation; SuperPro Designer; Renewable Energy; Methane

1. Introduction

Energy is a fundamental driver of global prosperity, yet the heavy reliance on fossil fuels has led to severe challenges including climate change, environmental degradation, and public health problems. With global energy consumption steadily increasing, particularly in rapidly developing countries, the urgent need for alternative and sustainable energy sources has become evident [1]. Biogas has emerged as a promising renewable option due to its environmental benefits and cost-effectiveness compared to other renewable sources [2]. Biomass-based technologies are expected to play a vital role in meeting future energy demands because of the abundance, diversity, and versatility of biomass resources, which can be transformed into heat, power, chemicals, and biofuels [3]. Biological wastes, once considered low-value materials, are increasingly recognized as valuable feedstocks for eco-friendly fuel production, contributing to the global transition from petroleum-based to bio-based economies [1, 4]. Anaerobic digestion (AD) of complex organic matter proceeds through a series of successive stages, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Among these, hydrolysis is frequently the rate-limiting step, particularly when the particulate material is resistant to degradation or when systems operate under high loading conditions. Although the hydrolysis kinetics of certain

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individual substrates has been characterized, the process is generally modeled as a simple first-order reaction due to the considerable variability in substrate composition. [9]. Among renewable energy sources, (AD) offers a particularly efficient pathway for converting organic waste into biogas, mainly methane, through microbial activity in oxygen-free environments [5]. However, the process is highly sensitive to factors such as temperature and feedstock composition, as methanogen bacteria function only within specific conditions [6]. Biogas production can rely on a wide range of feedstocks, including agricultural residues, animal manure, energy crops, industrial byproducts, and municipal organic wastes [7, 8]. Animal manure and plant residues are among the most widely used, while energy crops and grasses provide promising yields with additional environmental benefits. Industrial and municipal organic wastes, when properly segregated, also serve as efficient substrates, thereby reducing pollution while producing renewable energy. Overall, the use of biogas not only provides a sustainable alternative to fossil fuels but also contributes to waste management, greenhouse gas mitigation, and energy security. Super Pro Designer is a useful tool for scientists and engineers working in manufacturing, process engineering, and process development. Additionally, it is a useful tool for experts working on environmental concerns (e.g., pollution prevention, waste minimization, air pollution management, wastewater treatment). Super Pro offers environmental impact assessment, project economic evaluation, and modeling of manufacturing and end-of-pipe treatment processes under one roof. [10]. The objective of this study is to develop and optimize an industrial-scale anaerobic digestion process for biogas production from cow dung, aiming to maximize methane yield, enhance renewable energy generation, and contribute to sustainable waste management and environmental pollution reduction.

2. Materials and Methods

2.1. Materials

In this study, cow dung was used as a feedstock for methane production via anaerobic digestion, a process that decomposes biomass in the absence of oxygen. Cow dung is rich in organic matter and essential nutrients, making it an ideal substrate for microbial activity. Its color ranges from greenish to dark brown or black, darkening upon exposure to air due to oxidation and drying.

- **Properties of Cow Dung:** Cow dung is a suitable substrate for biogas production due to its rich organic content, which can be broken down by anaerobic microbes to produce methane. Its effectiveness depends on factors such as the cow’s diet, age, and manure composition.
- **Organic Matter Content:** Cow dung contains carbohydrates, proteins, and lipids that support microbial activity. Higher carbohydrate levels generally enhance biogas yield. Volatile Solids (VS) indicate the digestible organic matter available.
- **Water Content:** Cow dung has high water content, supporting microbial activity in anaerobic digestion. Excess water, however, can raise heating and transport costs.
- **Nutrient Content:** Cow dung is rich in nitrogen, phosphorus, and potassium, making the digestate a valuable fertilizer. Nutrient levels can be optimized through proper digestion and slurry management.

2.2. Presence of Microbes

Cow dung naturally contains a variety of bacteria and other microorganisms that play a crucial role in the anaerobic digestion process. These microbes break down the organic matter into biogas components.

2.3. Factors Affecting Biogas Production

2.3.1. Cow's Diet

The diet of the cows significantly impacts the composition of their manure and, consequently, the biogas yield.

2.3.2. Cow's Age and Health

Younger cows may produce manure with higher biogas potential due to differences in their digestive processes.

2.3.3. Temperature

Anaerobic digestion is temperature-sensitive, with mesophilic (moderate temperature) and thermophilic (high temperature) conditions being common for cow dung digestion.

2.3.4. pH

The pH of the cow dung slurry needs to be maintained within a suitable range for optimal microbial activity and biogas production.

2.3.5. C/N Ratio

The carbon-to-nitrogen ratio in the substrate is also important for efficient digestion.

2.4. Benefits of Cow Dung for Biogas Production

2.4.1. Renewable Energy Source

Biogas production from cow dung provides a renewable energy source, reducing reliance on fossil fuels.

2.4.2. Waste Management

It helps in the management and disposal of animal waste, reducing environmental pollution.

2.4.3. Fertilizer Production

The digestate from biogas production can be used as a nutrient-rich fertilizer, improving soil fertility and reducing the need for synthetic fertilizers.

2.4.4. Greenhouse Gas Reduction

Biogas production can help reduce greenhouse gas emissions, particularly methane, and a potent greenhouse gas.

2.4.5. Equipment

- **Feeding and Mixing Unit:** Receives cow dung and mixes it with water to adjust the slurry consistency before feeding into the reactor.
- **Anaerobic Digester (Main Reactor):** Continuous Stirred Tank Reactor (CSTR)**:** Performs anaerobic digestion of biomass to produce biogas (mainly methane and carbon dioxide).
- **Degasification Unit:** Degasifier**:** Removes trapped gases from the liquid phase, allowing biogas separation.
- **Gas Compressor**: Increases the pressure of the produced biogas to prepare it for storage in pressurized tanks or for pipeline transport. Compression is essential to reduce volume and facilitate downstream handling or bottling.

2.5. Methods

2.5.1. Process Description: Biogas Production from Cow Manure

Biogas production from cow manure is achieved through anaerobic digestion in a continuous stirred tank reactor (CSTR). Fresh manure, rich in biodegradable organic matter, is diluted with water (3–5% solids) to enhance flow and microbial activity. The mixture is preheated to 37 °C and fed into a mesophilic digester (35–37 °C). Under anaerobic conditions, microorganisms convert the organic matter through hydrolysis, acidogenesis, acetogenesis, and methanogens. After a hydraulic retention time of about 15 days, the produced biogas typically contains 55–65% methane, 30–40% carbon dioxide, and traces of hydrogen sulfide and moisture. The collected gas undergoes purification to remove H_2S, water vapor, and CO_2 before utilization.

2.6. Process Description in SuperPro Designer Software

2.6.1. Open SuperPro Designer

- Start > All Programs > Super Pro Designer 4.53 >SuperPro Designer v 4.53
- Select the continuous in Plant Operation Mode window and click (OK)

The following figure (1) , The overall chart of this study is represented in the figure (1) bellow

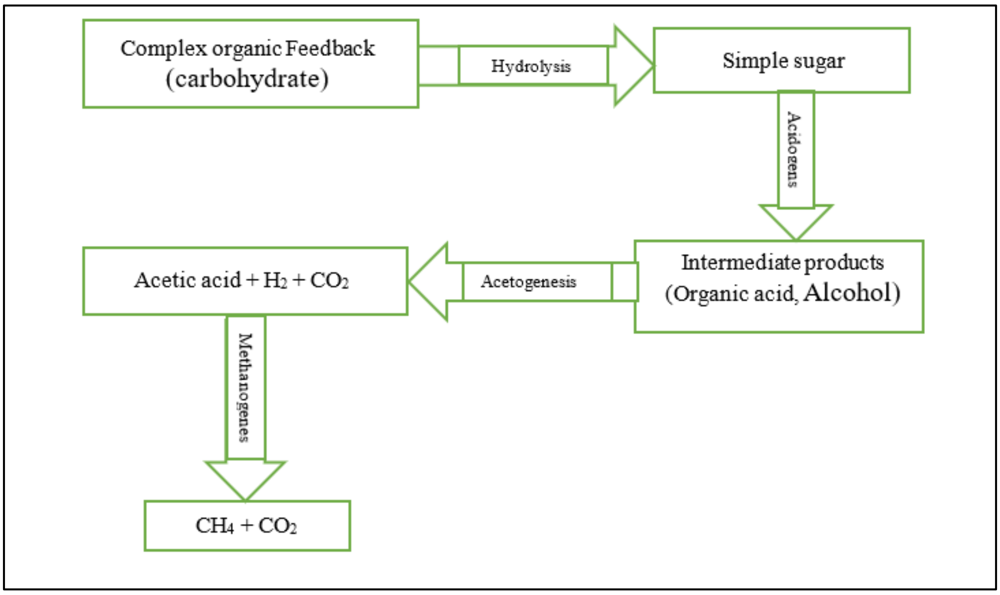

Figure 1 Overall flowchart of the study

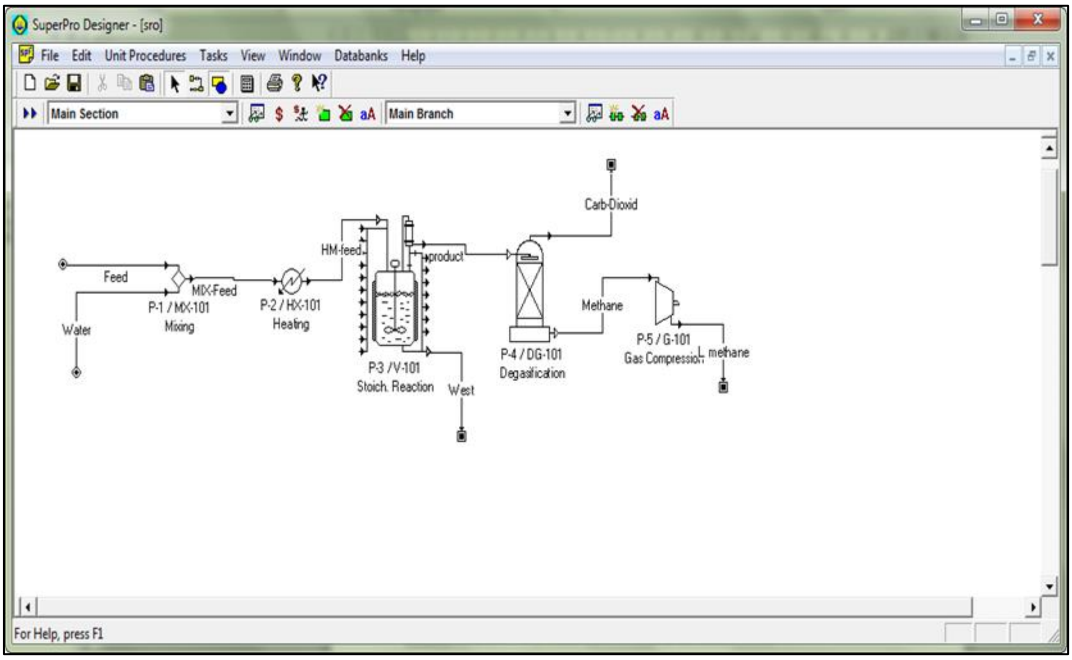

Figure 2 The add Streams to the units operation using SuperPro Designer Software (Version 4.53)

3. Results and Discussion

3.1. Results and Discussions of Work

In this section, the results obtained from the experiment in the Super Pro program will be presented and listed.

Table 1 The chemical and physical properties of cow dung

Component	Content (dry weight)
Total Solids (TS)	100 %
Volatile Solids (VS)	70 – 80 %

Fixed Solids (Ash)	20 – 30 %
Carbon (C)	35 – 45 %
Hydrogen (H)	4 – 6 %
Oxygen (O)	30 – 40 %
Nitrogen (N)	1.5 – 2.5 %
Phosphorus (P)	0.4 – 0.8 %
Potassium (K)	0.5 – 1.5 %
Sulfur (S)	0.2 – 0.5 %
C/N Ratio	20 – 30 %
pH	6.5 – 7.5 %
Moisture Content	10 – 15 %
Bulk Density	400 – 600 kg/m^3
Specific Heat Capacity	1.4 – 1.7 kJ/kg·K
Thermal Conductivity	0.15 – 0.25 W/m·K
Color	Light brown to dark

Table (1) summarizes the chemical and physical properties of dry cow dung. It contains 100% total solids, with 70–80% volatile solids, indicating high organic content for anaerobic digestion. Fixed solids (20–30%) represent inorganic minerals. Elemental composition includes C (35–45%), H (4–6%), O (30–40%), with smaller amounts of N (1.5–2.5%), P (0.4–0.8%), K (0.5–1.5%), and S (0.2–0.5%). The C/N ratio of 20–30 and pH of 6.5–7.5 are optimal for microbial activity. Moisture content is 10–15%, bulk density 400–600 kg/m^3, specific heat 1.4–1.7 kJ/kg•K, and thermal conductivity 0.15–0.25 W/m•K. Color varies from light to dark brown. These properties make cow dung suitable for biogas production, composting, and biomass energy applications.

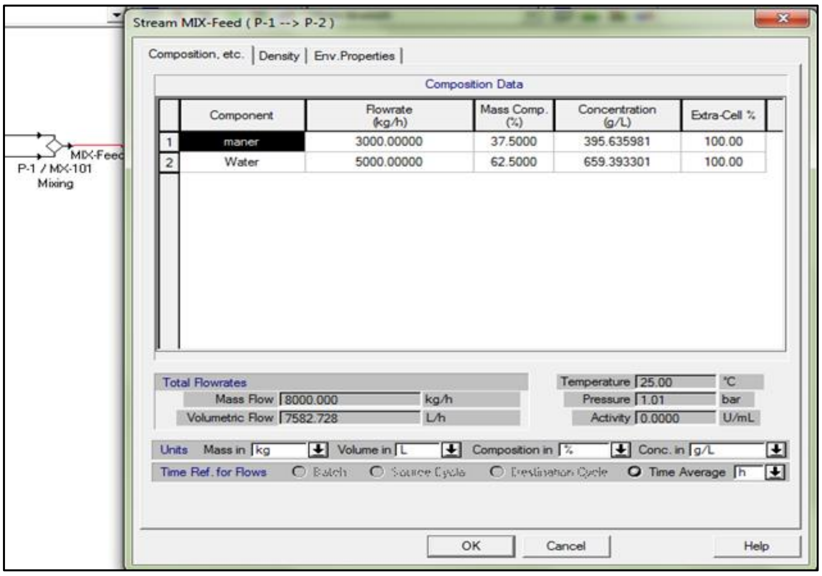

Figure 3 The results of the process for the mixer in SuperPro Designer

Figure (3) shows that the MIX-Feed stream (P-1 to P-2) is a binary mixture of "maner" (3000 kg/h, 37.5%) and water (5000 kg/h, 62.5%). Water acts as the main solvent, producing a homogeneous solution with concentrations of 395.64 g/L for "maner" and 659.39 g/L for water, ensuring stable and efficient downstream processing.

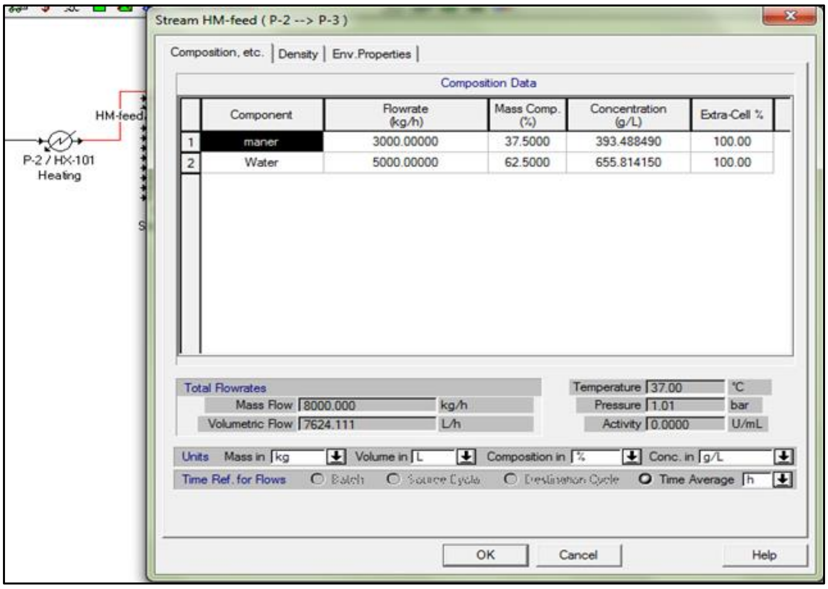

Figure 4 The results of the process for the heat exchanger in SuperPro Designer

Figure (4) shows HX-101 output, where the HM-feed stream (P-2 → P-3) with maner (3000 kg/h, 37.5%) and water (5000 kg/h, 62.5%) is preheated from 25 °C to 37 °C. Total mass remains 8000 kg/h, volumetric flow rises to 7624.11 L/h, and concentrations slightly adjust (~393.5 g/L maner, ~655.8 g/L water) at 1.01 bar, indicating effective preheating for improved downstream performance.

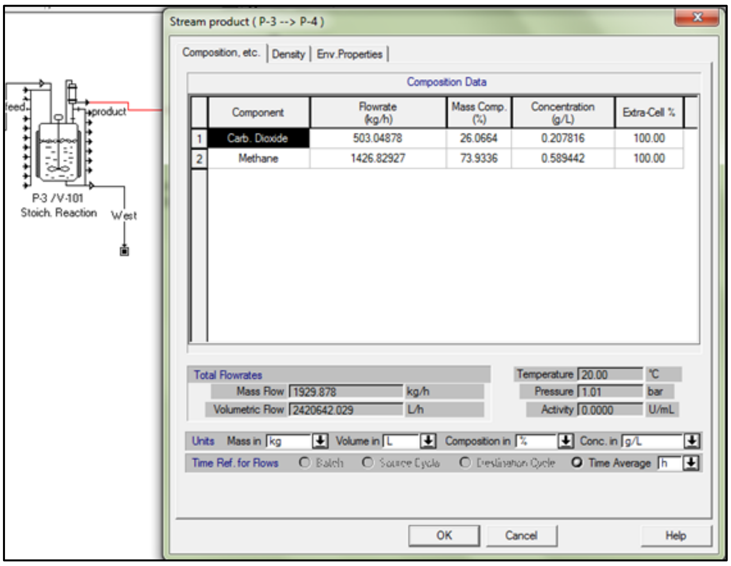

Figure 5 The results of the reactor for the mixer in SuperPro Designer

Figure (5) presents the reactor (V-101) output stream (P-3 → P-4) in SuperPro Designer. The gaseous product consists of methane (1426.83 kg/h, 73.93%) and carbon dioxide (503.05 kg/h, 26.07%), with a total mass flow of 1929.88 kg/h and a high volumetric flow of 2,420,642 L/h. Concentrations are 0.589 g/L for methane and 0.208 g/L for carbon dioxide. The stream exits at 20 °C and 1.01 bar, indicating near-ambient conditions. Methane dominates the composition, highlighting efficient gas production suitable for energy recovery or purification

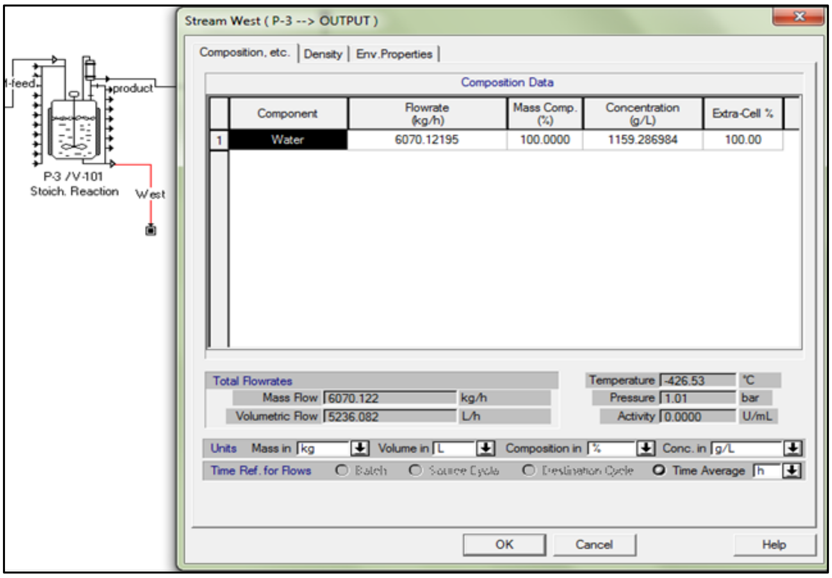

Figure 6 The results of the process for the reactor in SuperPro Designer

Figure (6) shows the reactor output stream in SuperPro Designer, highlighting the gaseous products of the reaction. The stream is composed mainly of methane (1426.83 kg/h, 73.93%) and carbon dioxide (503.05 kg/h, 26.07%), with a total mass flow of 1929.88 kg/h and a high volumetric flow of 2,420,642 L/h due to the low gas density. Gas concentrations are 0.589 g/L for methane and 0.208 g/L for carbon dioxide. Operating at 20 °C and 1.01 bar, the results indicate that methane is the dominant product, confirming efficient methane generation suitable for biofuel or energy production.

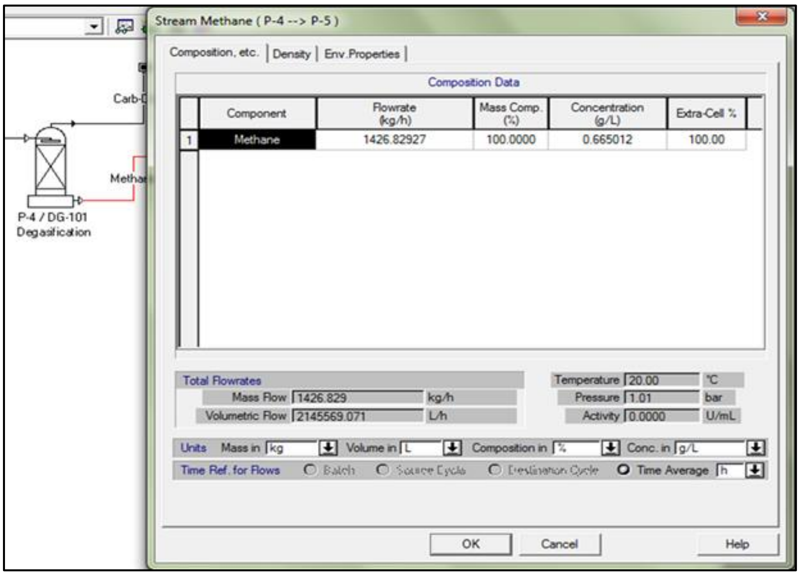

Figure 7 The results of the process for the degasification in Super Pro

Figure (7) shows the methane gas flow exiting the degasification process in SuperPro Designer. The gas has a mass flow of 1,426.83 kg/h with 100% purity, indicating complete separation from other components. Its concentration in the liquid phase is 0.665 g/L, and the volumetric flow is 2,145,569 L/h at 20 °C and 1.01 bar. These results demonstrate the high efficiency of the degasification process in producing pure methane under moderate operating conditions, ensuring effective gas purification for downstream use.

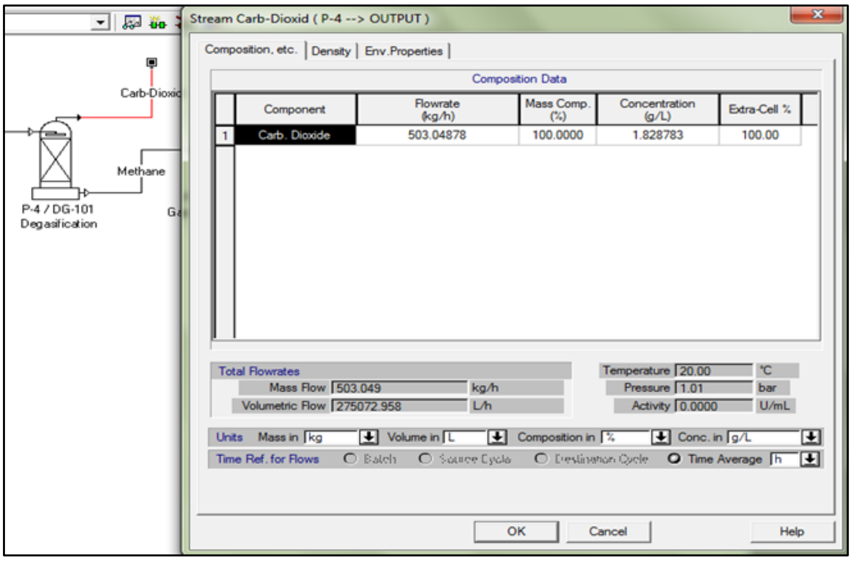

Figure 8 The results of the process for the degasifications in Super Pro

Figure (8) shows the output from the degasification unit DG-101 in SuperPro Designer. The stream consists entirely of carbon dioxide (503.05 kg/h, 100% of the composition), demonstrating highly efficient separation with no impurities. The CO_2 concentration is 1.83 g/L, and the volumetric flow is 275,072.96 L/h at 20 °C and 1.01 bar. These results confirm that the degasification unit effectively achieves complete and efficient CO_2 removal under safe and stable operating conditions.

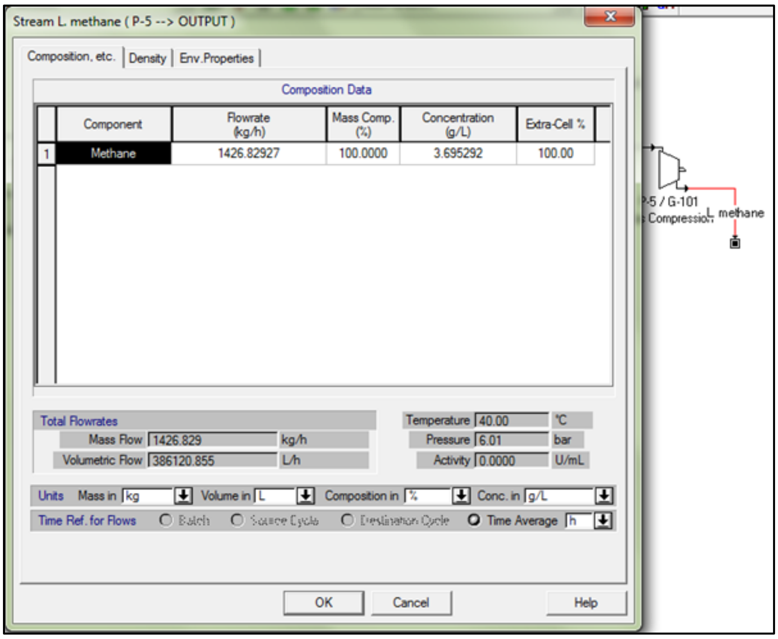

Figure 9 The results of the process for the compressor in Super Pro

Figure (9) shows the methane gas flow exiting the compressor unit in SuperPro Designer. The gas has a mass flow of 1,426.83 kg/h with 100% purity, a concentration of 3.70 g/L, and a volumetric flow of 386,120.86 L/h. Operating at 40 °C and 6.01 bar, the results demonstrate the compressor's high efficiency in transferring methane while maintaining complete purity without any impurities.

4. Conclusion

This study successfully simulated an industrial-scale anaerobic digestion process for biogas production from cow dung. Cow dung proved to be an effective substrate for producing high-purity methane (1,426.83 kg/h) while efficiently separating carbon dioxide. The process operated stably, demonstrating that cow dung can provide renewable energy, aid waste management, reduce greenhouse gases, and produce nutrient-rich fertilizer. These results highlight the feasibility and efficiency of large-scale biogas production from cow dung.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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