

**Research Article****Design of Anaerobic Co-Digestion and Integrated Fuzzy Logic Method for Optimization of Biogas Production from Mixed Livestock Waste**Sarwah Othman Ismael<sup>1,2,\*</sup> , Shuokr Qarani Aziz<sup>1</sup> <sup>1</sup> Department of Civil Engineering, College of Engineering, Salahaddin University-Erbil, Erbil, 44001, Iraq<sup>2</sup> Scientific Research Center, Salahaddin University-Erbil, Erbil, 44001, Iraq

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Article Info	Abstract
Article History Received Sep 18, 2025 Revised Mar 21, 2026 Accepted Mar 24, 2026	Anaerobic co-digestion of livestock waste presents a viable approach for addressing environmental challenges and reducing greenhouse gas emissions in semi-urban and rural contexts. This study focuses on the development of an optimised anaerobic digestion system for treating cow, sheep, and goat manure in the small Bnaslawra village, located in the Erbil Governorate of Iraq. Quantitative assessments of daily manure production were conducted to evaluate feedstock availability and guide the design parameters of the digester. The resulting system was engineered with a total volume of 836.96 m <sup>3</sup> and an organic loading rate of 4.42 kg volatile solids (VS) per cubic meter per day. To improve operational performance and enhance predictive reliability, a fuzzy-logic-based modelling framework was implemented in MATLAB R2023a. This computational model facilitated the identification of optimal process conditions and projected a daily biogas yield of approximately 2436.25 m <sup>3</sup> , of which methane constituted 1461.75 m <sup>3</sup> . The integration of systematic engineering design with intelligent modelling techniques underscores the potential of this approach for renewable energy production and sustainable waste management. The fuzzy logic model improves methane output estimation, supporting informed decision-making in waste-to-energy applications.
<b>Keywords</b> Design anaerobic co-digester Fuzzy logic model MATLAB R2023a software CH <sub>4</sub> production Bnaslawra village.	

**Copyright:** © 2026 Sarwah Othman Ismael, and Shuokr Qarani Aziz. This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY 4.0) license.**1. Introduction**

The industrial revolution's reliance on fossil fuels has accelerated greenhouse gas emissions and intensified climate change. Transitioning to renewable energy sources such as geothermal, hydro, solar, wind, and biomass is essential for achieving global sustainability goals Kasinath, et al. [1], [2]. Among these, anaerobic digestion offers a practical pathway to convert organic waste into bioenergy, reducing dependence on fossil fuels while mitigating environmental pollution[1].

In Erbil, Iraq, the rapid growth of livestock farming has increased manure generation, creating significant environmental challenges. Animal waste contributes to nonpoint source pollution, contaminates water bodies, and releases harmful gases such as carbon dioxide (CO<sub>2</sub>), hydrogen sulfide (H<sub>2</sub>S), and methane (CH<sub>4</sub>)[3]. These emissions pose risks to both human health and ecological systems. Proper management of livestock waste is therefore critical for sustainable rural development [4].

Biogas, primarily composed of CH<sub>4</sub> and carbon dioxide, is produced through anaerobic digestion of organic substrates. Common feedstocks include sewage sludge, municipal organic waste, food industry residues, and livestock manure [5, 6]. Anaerobic digestion supports the circular economy by recycling waste into renewable energy and nutrient-rich digestate, thereby reducing greenhouse gas emissions and promoting sustainable resource use [7, 8]. However, the efficiency of anaerobic digestion depends on several operational parameters, including digester design, temperature, hydraulic retention time (HRT), organic loading rate (OLR), substrate composition, and pH [9-12]. Anaerobic co-digestion, which combines multiple substrates, has been shown to improve methane yield by balancing nutrient ratios and enhancing microbial synergy [13-15].

Recent studies highlight the potential of co-digestion involving livestock manure and food waste, with promising results in CH<sub>4</sub> yield and process stability [16-18]. Factors such as temperature, pH, and substrate ratios significantly influence biogas production [19-22]. To optimize these complex interactions, artificial intelligence (AI) techniques have been increasingly applied. Fuzzy logic, neural networks, and hybrid models provide robust tools for predicting and controlling biogas production under variable conditions [23-25].

Zareei and Khodaei [26] employed an adaptive neuro-fuzzy inference system (ANFIS) to predict biogas yield from cow manure and maize straw. Optimal performance was achieved at a C/N ratio of 26.8, total solids of 9%, and moderate agitation, resulting in an 8% increase in methane output. To predict the rates of biogas production in a full-scale anaerobic wastewater treatment process, Huang, et al. [27] applied a fuzzy wavelet neural network (FWNN) with a genetic algorithm to predict biogas production in a full-scale wastewater digester. The FWNN achieved the highest accuracy ( $R^2 = 0.968$ ) compared with FNN (0.885), WNN (0.879), and NN (0.645), confirming its superior predictive performance. In addition, Rego, et al. [28] developed ANN and ANFIS models to predict biogas yield from swine sewage and rice husk. The ANFIS achieved higher accuracy ( $R^2 = 0.812$ ) than the ANN ( $R^2 = 0.777$ ). Similarly, Ikpe, et al. [29] applied ANFIS to optimize co-digestion of food waste and pig slurry, producing reliable yield predictions under optimal conditions. An IoT-based fuzzy logic controller for biogas digesters was developed by Pandian et al. (2021) and achieved 91% accuracy in predicting methane generation. Similarly, Fajobi, et al. [30] showed that fuzzy models enhance CH<sub>4</sub> yield and system stability by optimizing substrate ratios and operating parameters. Ling, et al. [31] combined genetic algorithms, fuzzy logic, and ANN for parameter prediction and real-time monitoring, recommending volatile suspended solids as an additional input to improve accuracy. By combining fuzzy logic with real-time monitoring of critical parameters, Swami, et al. [32] proposed an AI framework that improved methane output and stabilised digester performance under variable conditions. Farobie, et al. [33] further demonstrated that co-digestion of cow dung with *Ulva Lactuca* at a 2:1 ratio maximized CH<sub>4</sub> production.

Despite these advances, most studies focus either on digester design or on AI-based modelling in isolation. Few works integrate systematic engineering design with fuzzy-logic optimisation, particularly in rural mixed-livestock contexts where resource constraints and environmental pressures are acute.

This study addresses this gap by designing an anaerobic co-digestion plant for Bnaslawaw village, Erbil Governorate, and by applying fuzzy-logic modelling to estimate daily methane yield and identify optimal operating conditions. The integrated approach combines engineering calculations with intelligent modelling to support sustainable waste-to-energy solutions in rural and peri-urban areas.

## 2. Theoretical Outline and Design Calculation

### 2.1. Study Area and Data Collection

Before 1987, Bnaslawaw, south-east of Erbil's city centre, was a village. Bnaslawaw was known as Great or Big Bnaslawaw before it underwent multiple demolitions. Bnaslawaw Camp was established in 1987. A sub-district was created out of Bnaslawaw in 1997. Dashti Hawler (Erbil Plain) or Bnaslawaw District was the name of the district when it was established in 2002. Three sub-districts (Kasnazan, Daratoo, and Qushtapa) with 112 villages currently make up the Bnaslawaw District. 44° 0' 0" E to 44° 15' 0" and 35° 45' 0" to 36° 15' 0" are the coordinates of Bnaslawaw [34]. The collected data pertained to the small village of Bnaslawaw. It is located in the South-East of Erbil City, with coordinates 36.164881 N and 44.171970 E. It also has an area of 29 km<sup>2</sup>, with three sub-districts (Kasnazan, Daratwo, and Qushtapa) and a total of 112 villages (Figure 1). Data were collected on cows, sheep, and goats in the Directorate of Agricultural Bnaslawaw. Interviews and site visits were conducted, and data from related directories were used for data collection [35].

### 2.2. Biogas Plant Performance, Operational Boundaries and Maintenance

The performance of a biogas digester is strongly influenced by its design, which takes into account several factors. Resilience, airtightness, accessibility of local resources, and simplicity of use were all taken into account throughout the design phase [36]. The design specifications comprised:

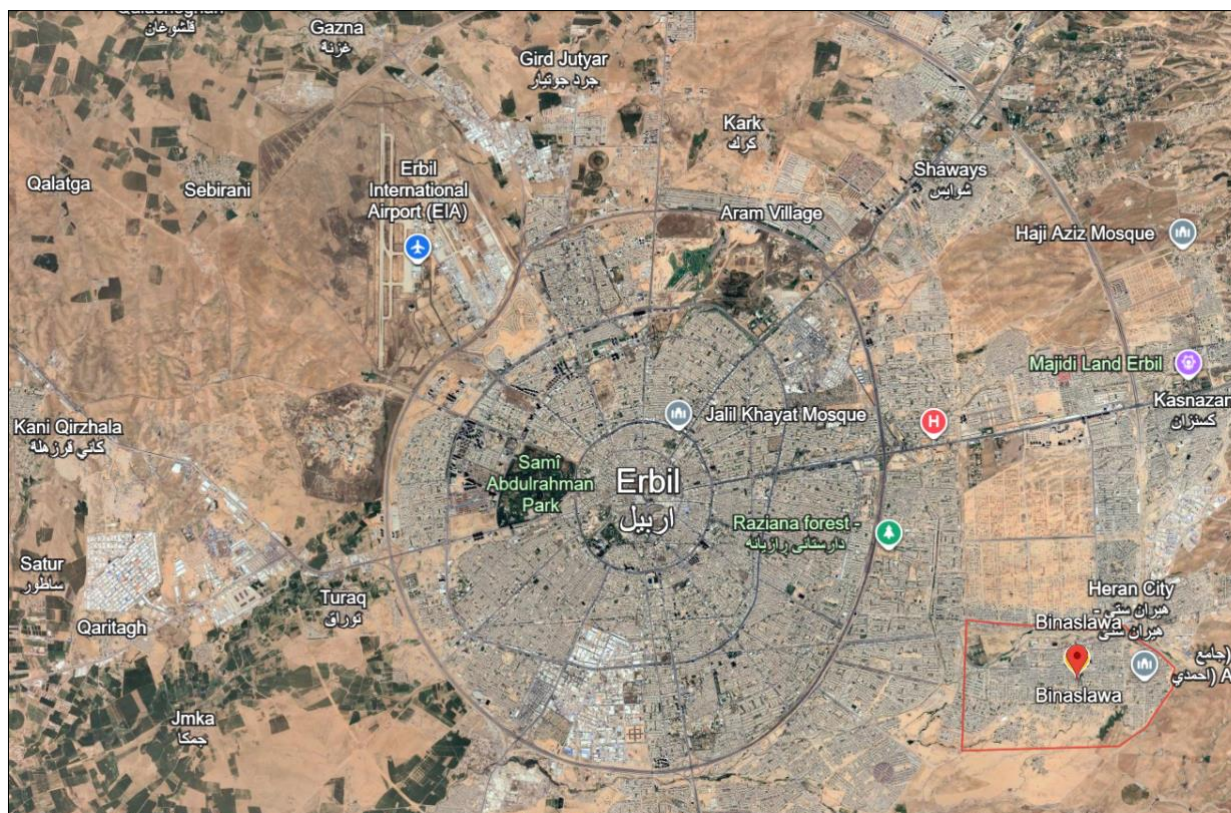
#### 2.2.1. Temperature

Biogas production is highly dependent on temperature; anaerobic digestion bacteria typically produce biogas at temperatures between 8 and 65 °C. Higher temperatures increase gas production rates and decrease anaerobic design retention times. The anaerobic design process can take place at different temperatures, divided into three temperature ranges: psychrophilic (below 20°C), mesophilic (30–42°C), and thermophilic (43–55°C) [37].

#### 2.2.2. Hydraulic Retention Time (HRT)

One of the most important design parameters for biogas digesters is the HRT, which establishes the typical time liquid sludge spends in the digester. The feedstock, bacterial population, and reactor parameters

all affect how quickly things break down. A longer retention period is required to prevent the number of microbes exiting the digestate from exceeding the number proliferating, and an increase in organic load lowers HRT. Since anaerobic bacteria normally multiply over 10 days, a short HRT period may result in poor gas output. It is crucial to adjust the HRT to the specific substrate breakdown rate to determine the required digester volume [37].



**Figure 1.** Bnaslaw district- Erbil governate study area from google earth map (Untitled project - Google Earth).

There is a direct relation between the process temperature and the HRT. The biogas production rate increases with increasing process temperature (Table 1).

**Table 1.** Biogas production thermal stage and their corresponding retention time [37].

Thermal stage	Process Temperature	Minimum HRT
Psychrophilic	< 20° C	70–80 days
Mesophilic	30–42° C	30–40 days
Thermophilic	43–55° C	15–20 days

The reactor temperature has a major effect on the growth and survival of microorganisms. Anaerobic digesters have historically operated in the mesophilic zone, although thermophilic conditions have gained popularity recently due to their ability to promote faster reactions, greater organic matter breakdown, and cleaner digestate. However, thermophilic reactors may become less viable due to heat losses in northern latitudes.

### 2.2.3. pH

A key factor in controlling microbial activity and guaranteeing steady biogas production in an anaerobic digestion system is pH. The organisms that convert intermediate products into methane, known as methanogenic archaea, are extremely sensitive to pH changes and function best in the specific range of 6.8 to 7.2. Methanogenesis is impeded when pH falls below 6.5, usually as a result of the buildup of volatile fatty acids (VFAs). This results in lower biogas production and the possibility of system failure. On the other hand, ammonia toxicity can result from pH values that are too high (over 7.5), which further destabilizes the process. Sustaining microbial synergy and optimising methane output, particularly in co-digestion or fluctuating organic loading rate scenarios, requires maintaining a balanced pH through sufficient buffering capacity and real-time monitoring [38].

### 2.2.4. Carbon/Nitrogen (C/N) ratio

To reduce ammonia inhibition, the carbon-to-nitrogen ratio (C: N) is a crucial factor in substrate selection. The breakdown of nitrogenous compounds releases ammonia, a nutrient essential for microbial growth [39]. When ammonia concentrations exceed levels that the digester's microorganisms can tolerate, ammonia inhibition occurs. The ideal carbon-to-nitrogen ratio is 16:1 to 25:1. Ratios that are too high or too low will affect biogas output [40].

### 2.2.5. Organic loading rate (OLR)

The amount of total volatile solids (TVS) produced per unit volume of biodigester per unit time is known as the OLR and is expressed in kg VS/m<sup>3</sup>/day. Excessive OLR values require more bacteria and may lead to acidification, lowering pH and damaging methanogenic bacteria. An essential operating parameter is the organic load, which indicates the volume and time required to feed dry organic matter into the digester [41].

### 2.2.6. Total solid contents of organic materials

The assumed TS value of 17% for fresh manure is based on regional livestock management data from the Directorate of Agriculture, Erbil (2023), and the Ministry of Agriculture and Water Resources. The target TS of 8% aligns with recommended dilution ranges for stable digestion [36]. Seasonal variations may cause fluctuations, but the design accounts for average conditions.

CH<sub>4</sub> production from animal dung varies globally due to factors like diet, digestion, management style, manure storage method, and gut microorganisms. Goat manure has the highest CH<sub>4</sub> production due to its high TS content and buffering capacity. Cow dung, with a higher TS content of 92.6%, produces less methane than chicken manure. Cow manure produces the least methane due to its higher lignin content (11.5%). All animal manures have pH values between 6.4 and 8.6, with cow and sheep manure having the highest values (8.6 and 8.1, respectively). These pH levels significantly enhance methanogenesis and the

activity of hydrolytic enzymes[42, 43]. Table 2 provides an extensive analysis of various animal manures and the CH<sub>4</sub> they produce [44].

**Table 2.** The physicochemical features and CH<sub>4</sub> generation of several animal manures[44].

Animal Manure	pH	TS (%)	VS (%)	C/N Ratio	CH <sub>4</sub> Yield (m <sup>3</sup> /KgVS)
Cow Manure	7.1–8.6	14.5–22.7	11.9–72.0	14.59–18.9	0.16- 0.4
Sheep Manure	7.16–8.1	22.3–40	18.7–72.7	11.3–14.7	0.207- 0.57
Goat Manure	7.9	33.7–55.5	27.7–89.4	18.0	0.402- 0.65
Chicken Manure	6.9–7.4	20.0–92.6	18.3–84.1	7.5–9.75	0.16–0.396

The following variables affect the generation and final product of biogas: temperature, toxicants, loading time, feedstock composition, residence time, mixing, stirring, pH, and oxidising conditions. Among the difficulties are financial aid and a shortage of technical expertise. There must be a comprehensive policy governing the design, construction, use, and sale of biodigesters to promote the use of biogas and its sustainable application. Important instruments include inexpensive biodigesters, biogas education, and an environment with favorable laws and policies [45].

### 2.3. Biogas Plant Design and Sizing Calculation

Anaerobic digestion plant planning involves assessing the digestion volume required and the technology to be used in the biogas plant. The selection and examination of feedstocks is crucial, including their availability, quality, and potential future developments. A thorough understanding of the substrate, including available quantity, frequency, quality, and parameters such as HRT, OLR, and digestive temperature, is essential. The volume computation is performed after selecting other plant settings and operating conditions, including available feedstocks. The process conditions, such as temperature, volume, reactor management, and technology, are also considered. The values of HRT and OLR, along with the co-digestion types, should be considered, as co-digestion can increase biogas production. The process should consider factors such as batch and continuous processes, as well as co-digestion methods [46].

The following calculations provide the quantitative foundation for the design of a biogas co-digestion plant for a mixed livestock population. This process, as outlined in [47], is divided into three primary stages: waste quantification, volume determination, and geometrical dimensioning.

#### 2.3.1. Total Waste Quantification and Total Solids (TS) Calculation

This stage focuses on converting animal population data into a usable measure of total daily feedstock, accounting for TS concentration. This is the initial step, in which the total daily waste mass is determined by summing the contributions from each animal type.

The design process was conducted sequentially, beginning with quantifying the available substrate and culminating in determining the digester's physical dimensions. Table 3 provides a clear basis for evaluating the amount of manure input and ensures the repeatability of the study's starting parameters for

an academic audience. It also acts as the main data set for all further computations.

$$\text{Total Daily Waste (kg/day)} = N \times W \quad (1)$$

where:

N: Number of Animals.

W: Daily Waste Production per Animal (kg/day).

**Table 3.** Summary of study area: Input Animal Data.

Animal Type	Number of Animals	Daily Waste Production per Animal (kg/day)	Total Daily Waste Production (kg/day)
Cows	167	10	1670
Goats	803	1.55	1244.65
Sheep	2757	1.8	4962.6

- Total Waste = 1670 + 4962.6 + 1244.65 = 7877.25 kg/day

In addition, the TS content is a critical parameter for digester performance. A TS content of 17% is assumed for the fresh waste.

- Total TS = 7877.25 kg/day × 0.17 = 1339.13 kg

To ensure optimal anaerobic digestion, the influent TS concentration is targeted at 8%. The total required influent volume is then calculated by diluting the total solids.

- Total Influent = (1339.13 kg)/0.08 = 16739.13 kg/day

**Table 4.** Assumptions for volume and geometrical dimensions [47].

Assumptions: For Volume	For Geometrical Dimensions
$V_c \leq 5\%V$	$D = 1.3078 \times V^{1/3}$
$V_s \leq 15\% V$	$V_1 = 0.0827 D^3$
$V_{gs} + V_f = 80\%V$	$V_2 = 0.05011 D^3$
$V_{gs} = V_H = 0.5 (V_{gs} + V_f + V_s) K$	$V_3 = 0.3142 D^3$
$K = 0.4 \text{ m}^3/\text{day}$	$R_1 = 0.725 D, R_2 = 1.0625 D$
	$f_1 = D/5, f_2 = D/8$
	$S_1 = 0.911 D^2, S_2 = 0.8345 D^2$

The equations presented in Table 4 are adapted from [47], which assumes cylindrical digesters of medium scale. Their applicability is limited to reactors with similar geometries and may not extend to very small or very large systems. This clarification ensures transparency in the design methodology and highlights the boundaries of formula validity.

### 2.3.2. Volume Determination

This stage uses the calculated influent volume to determine the necessary volumes of the digester and its associated chambers, based on HRT.

The working volume ( $V_{gs} + V_f$ ) is the portion of the digester where active digestion occurs. It is directly related to the total influent and the HRT, which is set at 40 days for a 30°C operating temperature.

$$\text{Working Volume} = \text{Total Influent} \times \text{HRT} \quad (2)$$

$$\text{Working Volume} = 16739.13 \text{ kg/day} \times 40 \text{ days} = 669565.2 \text{ kg or } 669.565 \text{ m}^3$$

The working volume typically accounts for 80% of the total digester volume (V), leaving room for a gas collection chamber and a sludge layer.

$$\text{Total digester Volume} = 669.565 \text{ m}^3 / 0.80 = 836.96 \text{ m}^3$$

The hydraulic chamber volume ( $V_H$ ) maintains a constant pressure and acts as an overflow. Its volume equals the gas storage volume ( $V_{gs}$ ), which is calculated using the gas production rate ( $K = 0.4 \text{ m}^3/\text{m}^3\text{d}$ ). The total working volume is assumed to be 95% of the total volume (V).

$$V_H = V_{gs} = 0.5 \times (0.95 \times V) \times K \quad (3)$$

$$V_H = 0.5 \times (0.95 \times 836.96 \text{ m}^3) \times 0.4 = 159.02 \text{ m}^3$$

To calculate the Scum Volume ( $V_c$ ), or the volume of the gas collecting chamber, the scum layer is a floating layer of solids that must be accounted for in the digester's design. It is typically a small percentage of the total volume.

$$V_c = 0.05 \times V \quad (4)$$

$$V_c = 0.05 \times 836.96 \text{ m}^3 = 41.848 \text{ m}^3$$

The sludge layer is a settled layer of solids at the bottom of the digester. The sludge volume ( $V_s$ ) can be determined using the relationship between the gas storage volume and the other digester components. where:

$$V_{gs} = V_H = 159.02 \text{ m}^3 \quad (5)$$

$$V_{gs} + V_f = 0.80 \times V = 669.568 \text{ m}^3$$

$$K = 0.4 \text{ m}^3/\text{m}^3\text{d}$$

The formula is:

$$V_{gs} = 0.5(V_{gs} + V_f + V_s) K \quad (6)$$

Now, substitute and solve for  $V_s$ :

$$159.02 = 0.5(669.568 + V_s) (0.4)$$

$$V_s = 795.1 - 669.568 = 125.532 \text{ m}^3$$

This result is within the recommended limit of 15%V (since  $125.532 \leq 125.544$ ).

### 2.3.3. Geometrical Dimensions

The physical dimensions of the cylindrical digester, including diameter (D) and height (H), were calculated using specific formulas provided in the reference material that relate these dimensions to the total volume (V).

$$D = 1.3078 \times V^{1/3} \quad (7)$$

$$D = 1.3078 \times (836.96)^{1/3} = 12.32 \text{ m}$$

$$H = 0.40 \times D = 4.93 \text{ m}$$

In addition, the radii of the top and bottom ( $R_1$  and  $R_2$ ) sections are calculated as a function of the diameter, as illustrated in Table 4.

$$R_1 = 8.93 \text{ m, and } R_2 = 13.10 \text{ m}$$

As well, the heights of the top and bottom ( $f_1$  and  $f_2$ ) sections are also a function of the diameter, as shown in Table 4.

$$f_1 = 2.46 \text{ m, and } f_2 = 1.54 \text{ m}$$

### 2.3.4. Detailed Volume and Surface Area Formulas

Based on the equations in Table 4, the calculated internal volumes of the digester ( $V_1$ ,  $V_2$ , and  $V_3$ ) are confirmed as follows:

$$V_1 = 154.71 \text{ m}^3, V_2 = 93.72 \text{ m}^3, \text{ and } V_3 = 587.72 \text{ m}^3$$

The surface areas ( $S_1$  and  $S_2$ ) of the internal components, which are useful for material estimation, can be determined according to the equations in Table 4.

$$S_1 = 138.28 \text{ m}^2, \text{ and } S_2 = 126.54 \text{ m}^2$$

## 2.4. Assessment of Biogas, Methane, and Carbon Dioxide Production Potential

The potential for producing  $\text{CO}_2$ ,  $\text{CH}_4$ , and biogas is evaluated using a systematic approach. The average values for  $\text{CH}_4$  yield and VS content for each type of animal manure are found in Table 2. It is expected that 60% of the total biogas produced is composed of  $\text{CH}_4$  and 40% is  $\text{CO}_2$ . For raw biogas made from animal manure, a 60:40 ratio [39, 48].

### 2.4.1. Calculation of Total Daily Volatile Solids (VS) Production and OLR

$$\text{Average VS (\%)} = (\text{Minimum VS\%} + \text{Maximum VS\%}) / 2 \quad (8)$$

- Cow Manure:  $(11.9 + 72.0) / 2 = 41.95\%$
- Goat Manure:  $(27.7 + 89.4) / 2 = 58.55\%$
- Sheep Manure:  $(18.7 + 72.7) / 2 = 45.7\%$

Total Daily VS Production (kg VS/day) is determined by multiplying the Total Daily Waste Production (kg/day) as illustrated in Table 3 by the average percentage of VS, divided by 100. This calculation is crucial as it converts the raw manure input into a measure of biodegradable substrate, which is essential for accurate volumetric calculations and for determining methane yield coefficients.

- Cows:  $1670 \text{ kg/day} \times (41.95 / 100) = 700.57 \text{ kg VS/day}$
- Goats:  $1244.65 \text{ kg/day} \times (58.55 / 100) = 729.02 \text{ kg VS/day}$
- Sheep:  $4962.6 \text{ kg/day} \times (45.7 / 100) = 2267.43 \text{ kg VS/day}$

$$\text{Total Daily VS Production} = 700.57 \text{ kg} + 729.02 \text{ kg} + 2268.04 \text{ kg} = 3697.63 \text{ kg VS/day}$$

An important stage in the calculating process is the transformation of the raw manure input into VS, the actual biodegradable substrate. Since CH<sub>4</sub> yield coefficients are usually reported in VS units, this conversion is essential for precise volumetric calculations, making it a crucial step. This clear illustration of the conversion improves the methodology's reproducibility and transparency[49].

$$\text{OLR} = \text{Total Daily VS Production} / \text{Total Digester Volume} \quad (9)$$

$$\text{OLR} = 3697.63 \text{ kg VS/day} / 836.96 \text{ m}^3$$

$$\text{OLR} = 4.42 \text{ kg VS/m}^3/\text{day}$$

The calculated OLR for the co-digestion process is 4.42 kg VS/m<sup>3</sup>/day

A sensitivity analysis was conducted to evaluate the impact of varying OLR on digester performance. At 3.5 kg VS/m<sup>3</sup>·day, the required digester volume increases to approximately 1050 m<sup>3</sup>, while the expected daily CH<sub>4</sub> yield decreases proportionally. At values above 4.42 kg VS/m<sup>3</sup>·day, risks of volatile fatty acid accumulation and pH reduction become significant, potentially destabilizing the process. These findings highlight the need for staged start-up and continuous monitoring when operating near the upper OLR range.

#### 2.4.2. Calculation Total Daily CH<sub>4</sub>, Biogas, and CO<sub>2</sub> Production (m<sup>3</sup>/day) for each animal type

Average CH<sub>4</sub> Yield (m<sup>3</sup>/kg VS) = (Minimum CH<sub>4</sub> Yield + Maximum CH<sub>4</sub> Yield) / 2.

- Cow Manure:  $(0.16 + 0.4) / 2 = 0.28 \text{ m}^3/\text{KgVS}$
- Goat Manure:  $(0.402 + 0.65) / 2 = 0.526 \text{ m}^3/\text{KgVS}$
- Sheep Manure:  $(0.207 + 0.57) / 2 = 0.3885 \text{ m}^3/\text{KgVS}$

Additionally, to determine total daily CH<sub>4</sub> production in (m<sup>3</sup>/day) by using equation (10) as follows:

$$\text{Total Daily CH}_4 \text{ Production} = \text{Total Daily VS Production} \times \text{Average CH}_4 \text{ Yield} \quad (10)$$

- Cows:  $700.57 \text{ kg VS/day} \times 0.28 \text{ m}^3/\text{KgVS} = 196.16 \text{ m}^3/\text{day}$
- Goats:  $729.02 \text{ kg VS/day} \times 0.526 \text{ m}^3/\text{KgVS} = 383.65 \text{ m}^3/\text{day}$
- Sheep:  $2267.43 \text{ kg VS/day} \times 0.3885 \text{ m}^3/\text{KgVS} = 881.94 \text{ m}^3/\text{day}$
- Overall Total CH<sub>4</sub> Production:  $196.16 + 383.65 + 881.94 = 1461.75 \text{ m}^3/\text{day}$

Likewise, determining the total biogas production (m<sup>3</sup>/day), the equation (11):

$$\text{Total Daily Biogas} = \text{Total Daily CH}_4 \text{ Production} / (\text{Assumed CH}_4 \% \text{ in Biogas} / 100) \quad (11)$$

- Cows:  $196.16 \text{ m}^3/\text{day} / 0.60 = 326.93 \text{ m}^3/\text{day}$
- Goats:  $383.65 \text{ m}^3/\text{day} / 0.60 = 639.42 \text{ m}^3/\text{day}$
- Sheep:  $881.94 \text{ m}^3/\text{day} / 0.60 = 1469.89 \text{ m}^3/\text{day}$
- Overall Total Biogas Production:  $326.93 + 639.42 + 1469.89 = 2436.25 \text{ m}^3/\text{day}$

Also, for calculating the total CO<sub>2</sub> (m<sup>3</sup>/day) production, equation (12) can be used:

$$\text{Total Daily CO}_2 = \text{Total Daily Biogas Production} \times (\text{Assumed CO}_2 \% \text{ in Biogas} / 100) \quad (12)$$

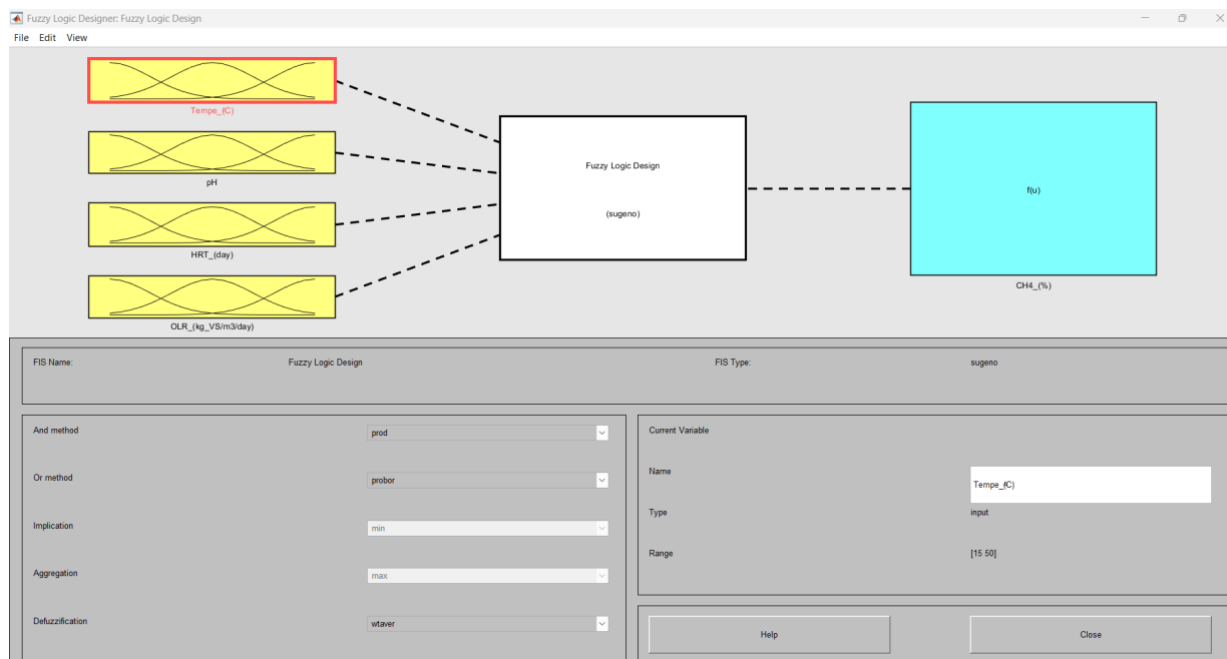
- Cows:  $326.93 \text{ m}^3/\text{day} \times 0.40 = 130.77 \text{ m}^3/\text{day}$
- Goats:  $639.42 \text{ m}^3/\text{day} \times 0.40 = 255.77 \text{ m}^3/\text{day}$
- Sheep:  $1469.89 \text{ m}^3/\text{day} \times 0.40 = 587.96 \text{ m}^3/\text{day}$
- Overall Total CO<sub>2</sub> Production:  $130.77 + 255.77 + 587.96 = 974.50 \text{ m}^3/\text{day}$

## 2.5. Fuzzy Logic Modelling

Accurate prediction of biogas yield is essential for optimizing waste-to-energy conversion systems. In this study, fuzzy-based modelling was implemented in MATLAB R2023a using the Fuzzy Logic model to forecast CH<sub>4</sub> yield and optimize co-digester performance. Fuzzy logic was selected for its ability to handle non-linear relationships and dynamic conditions in anaerobic digestion.

A first-order Sugeno fuzzy inference system (FIS) with linear output functions was employed. Four input variables, temperature (20–55 °C), pH (6.5–7.5), HRT (20–40 days), and OLR (3–5 kg VS/m<sup>3</sup>·day) were each represented by three triangular membership functions (Low, Medium, High). The output variable was the percentage of CH<sub>4</sub> in the biogas produced from cow, sheep, and goat manure in the co-digester.

Fuzzy rules were derived from literature-based optimal ranges [37-40] and expert judgment, ensuring consistency with established anaerobic digestion studies. No clustering or data-driven methods were applied; the rule base was constructed purely from expert knowledge. The weighted average of the rule outputs determined the final prediction[50]. A surface plot was generated to visualise the relationship between the input variables and CH<sub>4</sub> yield, as illustrated in Figure 2.



**Figure 2.** Input and output variables are considered for the present design of the co-digestion fuzzy model.

The process involved in fuzzy logic modelling is highlighted as follows:

- Define the inputs and output (linguistic variables) and terms (initialization)
- Convert the crisp variable to fuzzy sets (fuzzification)

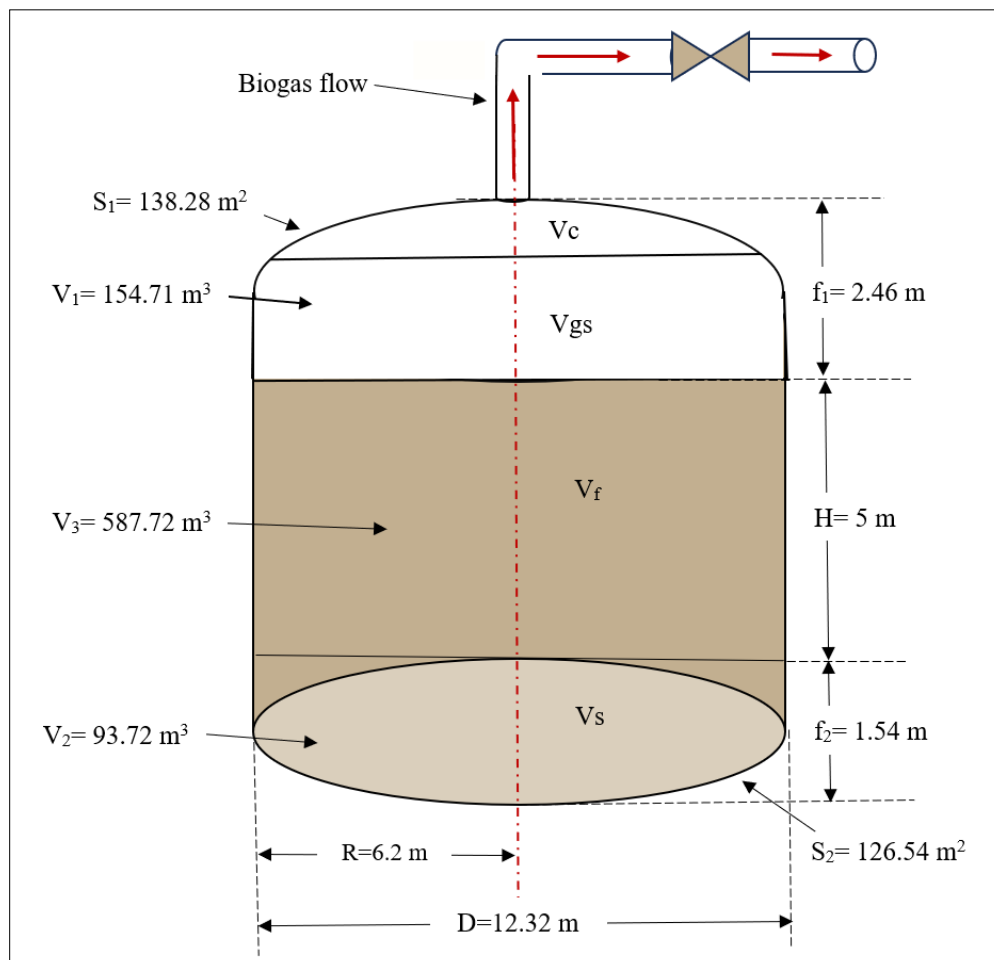
- iii. Create membership function (initialization)
- iv. Construct the rule base (initialization)
- v. Convert the output data to non-fuzzy values (defuzzification)

Figure 2 shows the MATLAB fuzzy logic design interface, where the four input variables (temperature, pH, HRT, and OLR) are connected to the fuzzy inference system and mapped to the output variable ( $\text{CH}_4$  yield). The interface illustrates the structure of the Sugeno-type fuzzy inference system, including membership function ranges, rule base configuration, and defuzzification settings, thereby providing a visual representation of how input–output relationships were modelled.

### 3. Results and Discussions

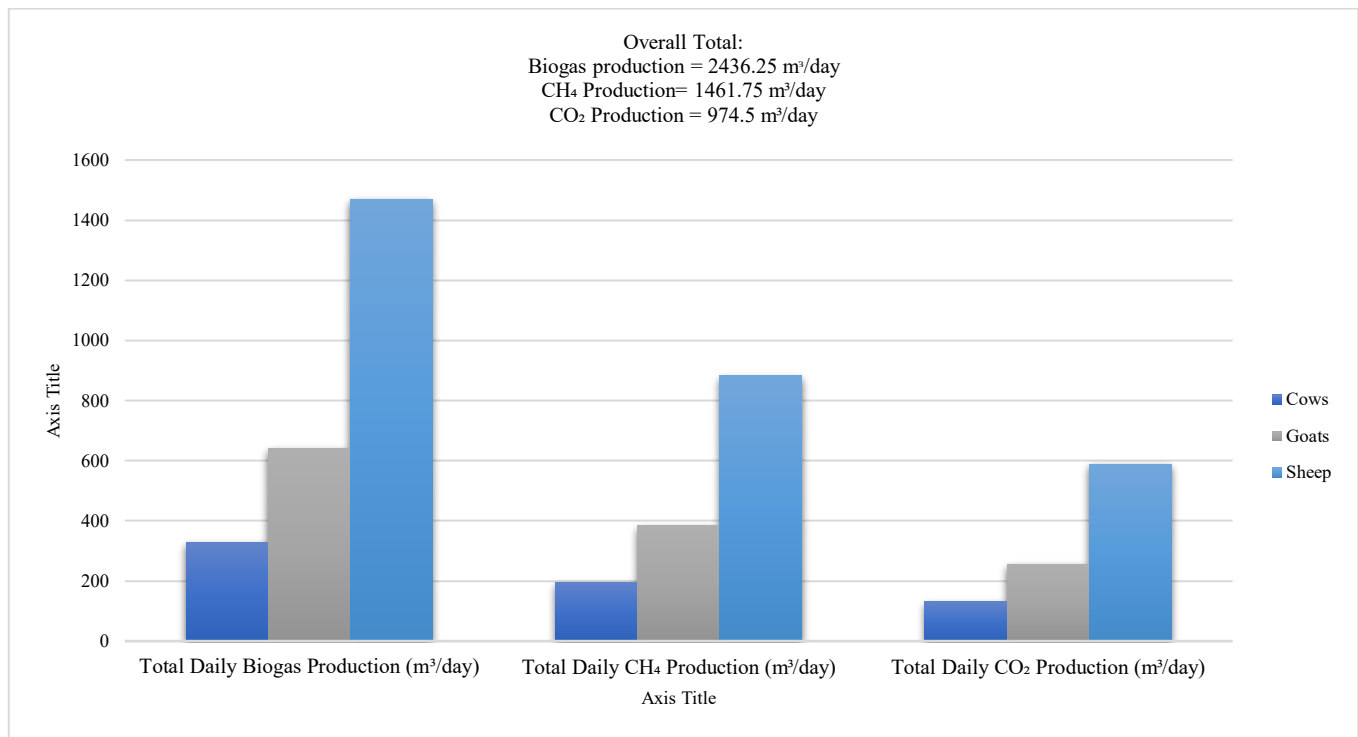
#### 3.1. Biogas production for designed co-digester

The study identified potential uses for a cylindrical anaerobic biogas co-digester in Bnaslawa, Erbil Governorate, as shown in Figure 3. It has an approximate overall effective volume of  $836.2 \text{ m}^3$ . A sustainable, long-lasting solution for waste management and renewable energy production in Erbil is provided by precise dimensions and configuration, optimised to achieve an appropriate hydraulic retention period and encourage sufficient mixing for mesophilic co-digestion of livestock waste.



**Figure 3.** Schematic of the anaerobic digester design and dimensions used for biogas production.

The estimated daily production of biogas (CH<sub>4</sub>) and CO<sub>2</sub> for the selected animal categories was calculated using the stated methodology and assumptions, as shown in Figure 4.



**Figure 4.** Estimated daily biogas, CH<sub>4</sub>, and CO<sub>2</sub> outputs from cows, goats, and sheep.

Based on these calculations, the chosen herd sizes (167 cows, 803 goats, and 2757 sheep) yield approximately 2436.25 m<sup>3</sup> of biogas per day, comprising 1461.75 m<sup>3</sup> of CH<sub>4</sub> and 974.50 m<sup>3</sup> of CO<sub>2</sub>. Sheep manure contributes the largest share due to both the high population (2757 animals) and substantial waste output (4962.6 kg/day), making it the most significant source of biogas and methane overall. Goats, however, demonstrate higher methane productivity per kilogram of volatile solids, underscoring their efficiency as a substrate. The relative proportions of CH<sub>4</sub> (≈60%) and CO<sub>2</sub> (≈40%) in the total biogas volume align with expected raw biogas composition, which typically ranges from 55–70% CH<sub>4</sub> and 25–30% CO<sub>2</sub>, thereby confirming the reliability of the estimates.

These production levels were achieved under an OLR of 4.42 kg VS/m<sup>3</sup>·day, which lies near the upper boundary of the recommended range of 2–5 kg VS/m<sup>3</sup>·day. This demonstrates that the digester has a capacity of 836.96 m<sup>3</sup> is the right size to handle all of the VS produced by the specified animal groups each day without being under- or overcapacity. Operating at this level can enhance methane productivity, but it also increases the risk of process instability if not carefully managed. To mitigate potential inhibition, a staged start-up strategy and continuous monitoring of key parameters, such as volatile fatty acids and pH, are essential. Excessive loading beyond the recommended range may lead to acidification, accumulation of intermediates, and suppression of methanogenic activity. Therefore, maintaining OLR within the optimal window is critical for balancing high biogas yield with long-term process stability.

By way of background, a comprehensive study of the anaerobic digestion of cow manure revealed OLRs ranging from 0.117 to 7.3 g VS/ L/ day (equivalent to kg VS/ m<sup>3</sup>/ day). Similarly, studies on pig manure have reported OLRs ranging from 0.9 to 15-42 grams of volatile solids per litre per day. According to studies, the OLR is either too low (less than 1 kg VS/m<sup>3</sup>/day) or too high (more than 4 kg VS/m<sup>3</sup>/day), even though these ranges are wide. The procedure may be either suppressed or overwhelmed, resulting in a decrease in methane production. With a value of 4.42 kg VS/m<sup>3</sup>/day, the calculated OLR is at the high end of the permissible range, suggesting that the system is very effective, even if Close monitoring will be necessary to maintain stability and optimise CH<sub>4</sub> output.

### 3.2. Scenarios for Optimization of CH<sub>4</sub> Yield via Fuzzy Rules

The intricate and unstable anaerobic co-digestion processes impact the breakdown of biomass. Taking into account several operational aspects and elements necessary for a successful CH<sub>4</sub> production process, the study employed a Fuzzy Logic model to assess non-linear processes and data. Successful CH<sub>4</sub> generation was ensured by the model's handling of data uncertainty and support for numerous input and output variables.

Designed to optimise CH<sub>4</sub> yield from anaerobic co-digestion, the developed Sugeno-type fuzzy inference system successfully captures the complex, non-linear correlations among important operational factors. Nine different rules, ranging from ideal conditions for maximum CH<sub>4</sub> output to unfavourable conditions that yield low output, show the system's performance across many operational scenarios. Each input variable was represented by three triangular membership functions: Low (L), Medium (M), and High (H). These linguistic terms capture the qualitative states of the parameters within their respective ranges. For example, temperature was categorized as L (20–30 °C), M (30–45 °C), and H (45–55 °C); pH as L (6.5–6.8), M (6.8–7.0), and H (7.0–7.5); HRT as L (20–25 days), M (25–35 days), and H (35–40 days); and OLR as L (3.0–3.5 kg VS/m<sup>3</sup>·day), M (3.5–4.0 kg VS/m<sup>3</sup>·day), and H (4.0–5.0 kg VS/m<sup>3</sup>·day).

These rules are designed to achieve a specific CH<sub>4</sub> yield by combining different input conditions. They represent the most critical relationships for optimization within the given parameter ranges, as demonstrated in Table 5.

The scenarios for rules (1 to 5) show the best CH<sub>4</sub> output. The main aim of the fuzzy logic model is to make the total CH<sub>4</sub> yield. The five rules are intended to maximise CH<sub>4</sub> production, based on well-established scientific principles of anaerobic digestion. Rule 1 in particular sets the bar for perfect performance:

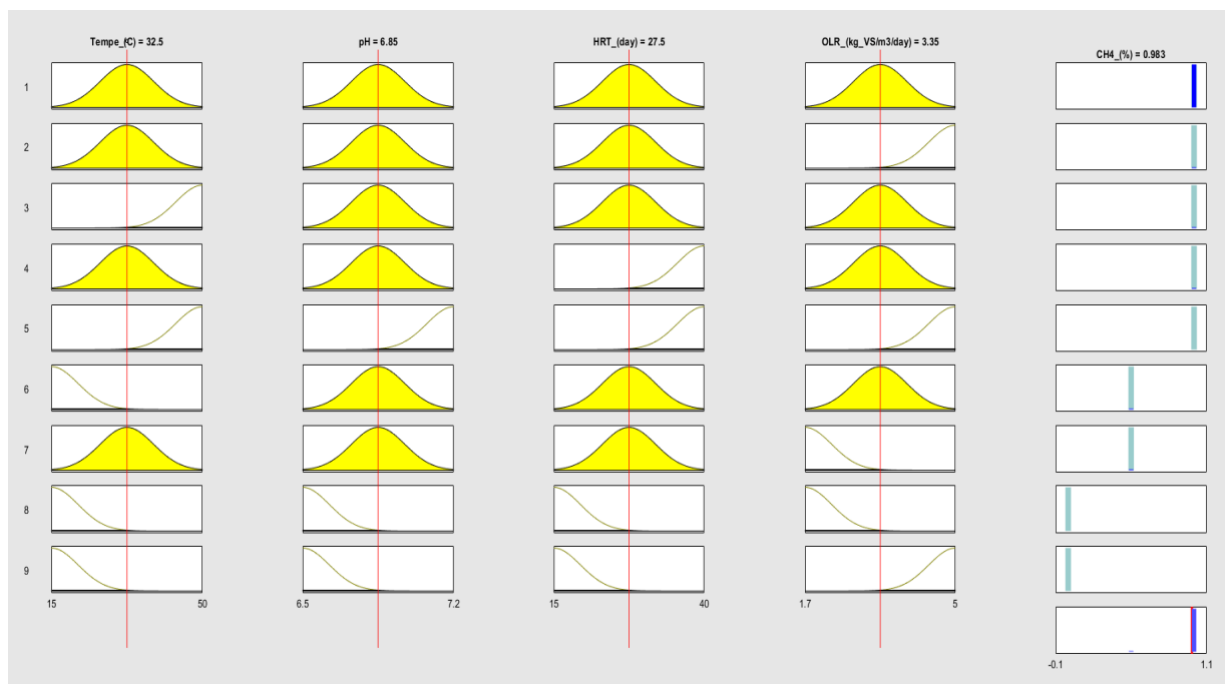
If (Temperature is M), (pH is M), (HRT is M), and (OLR is M), then CH<sub>4</sub> is H.

This rule reflects the best circumstances for a mesophilic anaerobic digester, which has a neutral pH of roughly 7 and a temperature of about 35 °C. A pH of 6.9 best supports the symbiotic interaction between

acidogenic and methanogenic bacteria. As shown in the fuzzy inference diagram for the percentage of CH<sub>4</sub> in Figure 5, the middle input values for all four parameters yield a high defuzzified output. In particular, a score of 0.983 on a normalised scale implies that the optimal biogas mixture should include roughly 70% of its components.

**Table 5.** Scenarios and rules-based for CH<sub>4</sub> prediction.

Rules	Scenarios	Input parameters				CH <sub>4</sub> (%) Output
		Temp. (C)	pH	HRT (day)	OLR (kg VS/m <sup>3</sup> /day)	
1	Optimal mid-range conditions	M	M	M	M	H
2	High Loading with Optimal Conditions	M	M	M	H	H
3	High Temperature with Balanced Conditions	H	M	M	M	H
4	Long retention time	M	M	H	M	H
5	Comprehensive high conditions	H	H	H	H	H
6	Sub-optimal Temperature	L	M	M	M	M
7	Balanced but Low Loading	M	M	M	L	M
8	All Parameters are Low	L	L	L	L	L
9	Unfavorable Overload with Poor Conditions	L	L	L	H	L



**Figure 5.** Visualization of the fuzzy inference system rule base, showing input conditions and predicted CH<sub>4</sub> yield.

The remaining high-yield rules (Rules 2, 3, 4, and 5) show the system's strength and the subtle relationships between variables. For instance, if temperature, pH, and HRT are maintained at optimal levels, Rule 2 predicts high CH<sub>4</sub> production even at high OLR. This recommends that the system can handle higher volumes without sacrificing effectiveness, which is crucial for industrial applications. Similarly, rules 3 and 4 show that, under the correct conditions, small changes in temperature or hydraulic

retention time may not always result in a decline in efficiency. Rule 5, which combines high values for all four inputs, reflects the upper limit of the system's operational ability under the given conditions and models a state of maximum metabolic activity and substrate conversion.

Suboptimal and low-yield scenarios (Rules 6, 7, 8, 9); the model also accurately reflects circumstances that result in reduced or negligible CH<sub>4</sub> production, offering insightful commentary on process failure and inhibition. Medium-yield rules (Rules 6 and 7) highlight the negative impact of a lone restricting element. Rule 6, which forecasts a medium CH<sub>4</sub> yield, indicates that a low temperature (15 °C), even with optimal conditions for the other factors, severely slows the methanogenic consortium's kinetic rates. In Rule 7, a low OLR is considered the limiting factor, suggesting that a limited supply of organic substrate prevents the system from reaching its maximum methane yield.

A low CH<sub>4</sub> output scenario predicted by Rules 8 and 9 is a major warning sign of system malfunction. The combined effects of low pH, cold temperature, and insufficient substrate result in minimal metabolic activity in Rule 8, where all variables are at their lowest levels. This results in a kinetically limited and deprived state. Particularly crucial is Rule 9: a high organic loading rate combined with low pH, low temperature, and low HRT might be hazardous. The rapid intake of organic materials in this case contrasts with the sluggish microbial conversion, resulting in the accumulation of VFAs and a subsequent drop in pH. This acidity inhibits methanogens and can lead to complete process failure, as the fuzzy-logic model accurately anticipated.

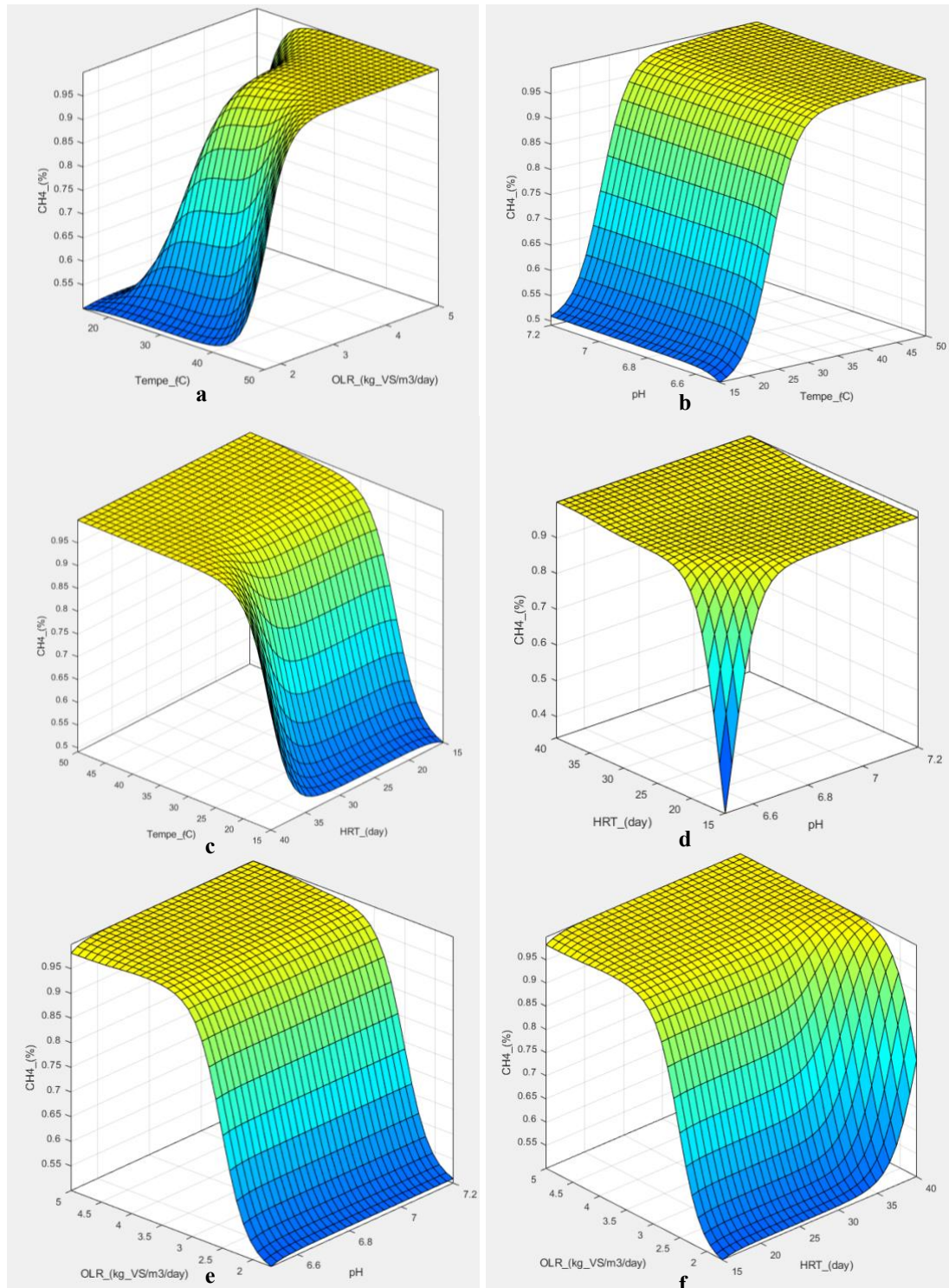
In conclusion, high-yield rules are used to establish optimal working conditions and demonstrate system stability. Automated systems can integrate the system's defuzzified CH<sub>4</sub> % output for real-time process monitoring, helping preserve high methane yield. Future studies could entail broadening the rule base, incorporating more intricate membership functions, and validating the model using long-term experimental data from a pilot-scale bioreactor.

### 3.3. Analysis of Surface Viewer Plots for CH<sub>4</sub> Optimization

The surface viewer plots generated from the Sugeno-type fuzzy inference system provide a comprehensive visualisation of the non-linear interactions between the input parameters (temperature, pH, HRT, and OLR) and the output CH<sub>4</sub>. The input-output model surface correlation, the dependence and interrelations of CH<sub>4</sub> generation on one or two input factors, and the combination of the input variables are all displayed in Figure 5. As a surface viewer, the FIS's output "CH<sub>4</sub> (%)" was plotted against the inputs "Inflow, Temp, pH, HRT, and OLR."

Taking the first scenario as an example, the surface viewer shown in Figure 6a reveals that high yield depends on ideal temperatures, but the system's response is complex. CH<sub>4</sub> production increases with OLR, but is sensitive to the right temperature. Even a good OLR isn't enough for high yield at low temperatures due to kinetic limitations on microbial activity. The synergistic relationship between temperature and pH

is demonstrated in Figure 6b, which shows temperature vs pH. The highest CH<sub>4</sub> production occurs when the temperature and pH are both within their optimal ranges: pH 7-8 and mesophilic temperatures 30-40 °C. The yield clearly decreases at low pH levels and low temperatures (below 25 °C). Methanogens' metabolic activity is heavily reliant on both a favourable temperature and a stable, non-inhibitory chemical environment, which supports this.



**Figure 6.** Three-dimensional surfaces illustrating non-linear interactions among operational parameters and their effect on CH<sub>4</sub> yield.

Additionally, Figure 6c shows the surface plot of the impact of temperature and HRT on a system's kinetic efficiency. High CH<sub>4</sub> production occurs when both are optimal, while a drop in temperature reduces yield by allowing slower microbial processes. At low HRT, a high temperature is required for efficient conversion of the substrate into CH<sub>4</sub>. Operators can adjust retention time accordingly. Also, to maximise CH<sub>4</sub> yield, it is imperative to understand the relationship between pH and HRT, as shown in Figure 6d. A high plateau exists between medium- to high-pH levels and HRT values. A pH below 6.6 results in a rapid decline in methane production, regardless of HRT. High methane production and process stability rely on a pH that is stable and about neutral. Likewise, in Figure 6e, an optimal pH is required for high OLR to be converted to CH<sub>4</sub>; therefore, the link between OLR and pH is crucial. Low pH acidifies the process, leading to failure. The yield's dramatic increase with increasing pH, especially at higher OLRs, underscores the need for pH control in a high-rate digester. Similarly, in Figure 6f, increased OLR coupled with sufficient HRT leads to higher CH<sub>4</sub> production. A low HRT results in a low methane yield because slow-growing methanogenic bacteria are washed away.

Surface viewer plots are diagnostic tools that provide a visual depiction of the complex interactions in a fuzzy logic model. They verify that the optimal methane yield is a balanced combination of conditions rather than a single parameter, and they evaluate system rules. Important performance limits are highlighted by the strong variations, especially in pH. Process operators are guided by these charts, which emphasise the importance of keeping pH and temperature within ideal parameters for maximum output. To avoid process instability and ensure a steady supply of renewable biogas, they can forecast operational changes, such as increasing the OLR, and support the development of robust control systems.

#### 4. Conclusion

This study presents the design and modelling of an anaerobic co-digestion system for mixed livestock residues (cow, sheep, and goat) from the Bnaslawia area in Erbil Governorate, Iraq. By integrating engineering design principles with a fuzzy logic-based computational framework, the work provides a comprehensive approach to sustainable waste treatment and renewable energy generation. The reactor, with a total capacity of 836.96 m<sup>3</sup> and operated under an OLR of 4.42 kg VS/m<sup>3</sup>·day, was projected to deliver a daily biogas output of 2436.25 m<sup>3</sup>, of which 1461.75 m<sup>3</sup> was CH<sub>4</sub>. The fuzzy inference system implemented in MATLAB R2023a effectively simulated non-linear process behaviour and identified optimal operating conditions, offering reliable predictions of CH<sub>4</sub> generation and overcoming the limitations of conventional linear modelling approaches.

However, the study is primarily based on theoretical design and fuzzy modelling without experimental validation of the digester at the site. The fuzzy model has not been calibrated against independent datasets and should therefore be considered a qualitative decision-support tool rather than a

fully validated predictive model. Future work should include pilot-scale or full-scale implementation, systematic data collection, and refinement of fuzzy rules and membership functions, with comparative evaluation against ANN, ANFIS, or other AI-based modelling approaches. Such efforts will enhance the robustness, applicability, and predictive accuracy of fuzzy modelling for biogas optimization.

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