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Application fuzzy DEMATEL methodology to investigate some technical parameters of biochemical methane potential (BMP) test produced vegetable waste anaerobic biogas

Veysi Başhan · Afşın Y. Çetinkaya

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Abstract As the transition to renewable energy systems is accelerating, anaerobic digestion, which is one of the methods of energy recovery from organic substrates, continues to be studied with great interest by scientists. Anaerobic digestion research and applications are mostly carried out with biochemical methane potential (BMP) tests to decide the methane potency of sewage sludge, energy crops, and organic wastes. Unlike long and costly continually reactor experiments, actually, BMP tests are cumulative and can be performed with a relatively low investment of materials, technical labor, and also time. For the BMP to give accurate results, the effect of all the tools and technical parameters used in the implementation of the BMP should be well understood. In such situations, it is very useful to apply fuzzy logic methods in multi-criteria decision-making stages when more than one parameter changes at the same time. Therefore, in this study, fifteen parameters were determined and analyzed with the fuzzy DEMATEL (decision-making trial and evaluation laboratory) method to understand the cause-effect mechanism of the technical parameters of BMP. As a result of these analyses, it was seen that the material of the reactor (r_i-c_j value of 0.55), the particle size (r_i-c_j value of 0.43), the effect of mixing (r_i-c_j value of 0.32), and the amount of the total solids (TSA) (r_i-c_j value of 0.25) had a high effect in the causal sense. It was observed that the first-order parameter (material of reactor) was 27% stronger than the second-order (the particle size) parameter in terms of causality. Likewise, the second-order parameter is 34% stronger than the third-order parameter (the effect of mixing) in terms of cause effect. In addition, it was understood that the most effective parameters in the mechanism of effect were pH (r_i+c_j value of 3.41), C/N ratio (r_i+c_j value of 3.26), and temperature (r_i+c_j value of 3.07), respectively. Besides, high methane yield is seen in mesophilic conditions. The average cumulative biogas yield of the reactor is 282.1 NmL/g VS. The highest percentage of methane formed in the biogas occurred on the 21st day. Briefly, this study is important to provide a facilitating way for researchers working on BMP to understand the cause-effect mechanism of system technical requirements.

Keywords Biochemical methane potential · BMP · Vegetable waste · Fuzzy DEMATEL

V. Başhan (✉)
Maritime Faculty, Department of Naval Architecture and Marine Engineering, Bursa Technical University, 16310 Bursa, Turkey
e-mail: veysibashan@gmail.com; veysi.bashan@btu.edu.tr

A. Y. Çetinkaya
Civil Engineering Faculty, Environmental Engineering Department, Yildiz Technical University, Istanbul, Turkey

Introduction

The rapidly increasing world population is one of the most significant factors underlying environmental issues. Due to population growth and the rapid depletion of traditional energy resources in parallel with

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this, these resources cause greenhouse gases, which forces societies to use their existing energy potential more effectively on the one hand and to find new energy sources on the other (Li et al., 2020). The type of energy called renewable energy has come to the fore as an alternative to fossil fuels in energy production (Qiao et al., 2011). The search for alternative and safe renewable energy sources that are not fossil-based has a high priority in many economies around the world. Due to the global population growth triggering rapid urbanization and industrialization, critical problems have arisen in solid waste disposal (Stürmer et al., 2021). Vegetable waste is usually a major portion of any municipal solid waste (MSWs). Biogas is mainly composed of CH_4 (50–75%) and CO_2 (25–45%), and when combusted with air mainly releases CO_2, water vapor, and nitrogen. Biomethane production is an alternative to natural gas, which is one of the renewable energy sources (O'Connor et al., 2021). Vegetable waste is a very important residue class because it is produced in significant quantities due to the high human requirements. In the literature, the subject of BMP has been investigated in a multi-faceted and detailed manner. Santos et al. (dos Santos et al., 2020) determined the kinetic parameters for scale-up and assessing the methane-producing potential of fruit wastes (passion fruit peel, orange, and cashew pulp). Abunde Neba et al. (Abunde Neba et al., 2020) developed an approach that combines reachable regions and fuzzy multi-criteria decision methods for the design of multistage anaerobic digesters without using a kinetic model and to model their optimal configuration. Ansari et al. (2017) determined the biomethane potential of dried powdered algae, heat-treated algae, lipid-extracted algae, and protein-extracted algae. Justesen et al. (2019) studied the development and validation of a new gas density-based method to measure BMP with minimal investment in materials and equipment. Seekao et al. (2021) used mechanical models based on Monod kinetics to define the experimental results acquired from co-digestion of palm oil mill effluent with chicken manure and crude glycerol. Konrad et al. (2021) compared and analyzed the efficiency of an automated measurement system for biogas flow with control performed by a programmable logic controller called SAMB with widely distributed commercial equipment for this purpose, namely automatic methane potential testing. Olabi et al. (2020) proposed an artificial intelligence-based methodology to improve methane production from waste paper, and during the fuzzy logic-based modeling and optimization process, beating time and feedstock/inoculum ratio were used as decision variables to maximize methane production. Ward et al. (2008) reviewed existing optimization techniques for anaerobic digestion and identified possible areas for improvement, including key design considerations of reactor configuration, type, strength and duration of mixing regime, and active substance retention. Optimization of environmental conditions inside the digester such as microbial biomass, temperature, pH, buffering capacity, and fatty acid concentrations in the reactor is analyzed. In a study by Casallas-Ojeda et al. (2020), the simultaneous incidence of two important variables in anaerobic digestion of food waste was evaluated: temperature (20, 35, and 55 °C) and head space (20, 35, and, 50%). These can affect the kinetics of the process, the pH, and thus the BMP. Diaz-Cruces et al. (2020) aimed to investigate the effect of lactate fermentation type on the BMP of tequila vinasse. During methanogenesis, all tested raw materials resulted in different BMP performances. Primary lactate fermentation (from carbohydrates to the lactate + acetate) resulted in the highest BMP (435.9 NmL CH4/g VS added) and methane production rate (105.8 NmL CH4/day). Choi et al. (2020) investigated the effect of carbon type and carbon to nitrogen (C/N ratios) on the anaerobic digestion properties of organic wastes. As a result of the study, it was determined that the lag phase was only affected by the carbon type ($p < 0.05$). Ammonia nitrogen was mainly affected by nitrogen concentration ($p < 0.05$), regardless of carbon type. Another result of the study showed that xylan is useful as a raw material to reduce the lag phase and ammonia is affected independently of nitrogen concentration. Bernacchi et al. (2014) carried out a study to screen for parameters affecting the growth to crop yield of a biological methane production process. The authors noted that $Y(x/CH_4)$ could be used to adjust the carbon flux of the bioprocess in an industrial application by reducing $Y(x/CH_4)$ to identify limiting or inhibiting conditions during media development tasks and also to improve the carbon balance of the reaction. Gunaseelan (2004) studied to determine methane conversion rates and BMP of 54 fruit and vegetable waste samples and eight standard biomass samples. It was found that the temperature did not affect the

ultimate methane yields of the mango peels, but the conversion kinetics were higher at 35 °C than at 28 °C. Chandrasekhar et al. (2021) conducted a study to evaluate the effect of three different pretreatment strategies, namely acid, alkali, and hydrothermal pretreatment, on the BMP of seven different date palm biomass. The authors found that chemical composition and lignocellulosic morphologies strongly influence methane yield. Gu et al. (2021) investigated the effects of wear ball mill pretreatment on food waste particle size, soluble chemical oxygen demand, BMP, and microbial community during anaerobic digestion based on grinding speed and time. The authors observed that the extended milling time did not significantly improve methane production. They stated that methane productions of 490, 510, and 500 mL/g-VS were observed when the grinding speed was fixed at 300 rpm and grinding times of 10, 20, and 30 min were applied, respectively. Ewunie et al. (2021) examined the effects of mechanical, steam explosion, and alkali pretreatment on the chemical composition and methane yield of Jatropha curcas fruit shell (JCFS) under various process conditions. The authors indicated that compared to the untreated sample, grinding the JCFS to a particle size smaller than 1 mm increased the methane yield by 74.23%, while in the optimum steam explosion pretreatment process (160 °C, 5 min), the methane yield increased by 54.75%. Giwa et al. (2021) evaluated the effect of mixing anaerobic co-digestion of food waste and black water to determine the BMP. The authors determined that kitchen waste, which has an equal mixing ratio of 50% v/v with black water, has the highest biochemical methane potential with 295.13 mL CH_4/g VS when digested together. It is understood from all these literature studies that it is very important to understand the causal and effectual relationships of the parameters affecting a BMP system with each other. In such cases, the experience of the experts in the subject is of great importance. For this reason, the fuzzy DEMATEL method is used in the literature to examine systems consisting of multi-criteria, complex, and frequently interacting parameters. It is a method used successfully in nearly all fields of science such as medicine (Suzan & Yavuzer, 2020), social sciences (Abdullah & Zulkifli, 2015), and in many different engineering fields (Başhan & Demirel, 2018; Başhan & Ust, 2019; Başhan et al., 2020; Tseng & Lin, 2009). In this context, the aim of this study is to evaluate the amount and quality of biogas produced from vegetable waste and also reveal the cause-effect relation of vital parameters of BMP by using fuzzy DEMATEL methods.

Materials and methods

Vegetable wastes (VW) were collected from İBB Bayrampaşa vegetable market (at 41°04′59.10″ N latitude, 28°90′28.40″ W longitude). All nutrients were crushed to a mean particle size of 1–2 mm by an electrical grinder (BB51, Retsch, Germany).

A sample of wet VW was weighted (W_{wet}) and dried in an oven at 105–110 °C until a constant weighted (W_{dry}) was achieved. Such process was measured in triplicate and total solid (TS) was then calculated with the mean value as given in Eq. (1)

$$TS\left(\%_w\right) = \frac{W_{dry}}{W_{wet}}.100 \quad (1)$$

The volatile solid (VS) composition of the VW was assumed to be equal to 83%. Experiments were performed in terms of triple batch testing for 32 days. In each series of experiments, the gram amount of VW was prepared to be 10 g VS/(l.d).

The inoculum and basal medium were prepared according to the method provided by Çetinkaya and Yetilmezsoy (2019). The batch experiments were performed in glass serum bottles with a total volume of 300 mL of which 80% was kept as working volume (feedstock + anaerobic granular sludge + basal medium) and the remaining 20% as headspace. Biogas was collected in gas collection bags (Sigma-Aldrich, Germany) for the determination of CH_4 content. Daily volume of biogas was measured with the help of gas syringe. The biogas composition was obtained using a gas chromatograph (Shimadzu® GC-2014, Kyoto, Japan) which has a TCD (thermal conductivity detector).

Analytical methods

The pH of samples was determined by using a HI98108 pHep + ® waterproof pocket pH tester with 0.01 pH resolution (Hanna Instruments, USA). TS and VS were measured according to procedure 2540 B of Standard Methods (APHA, 2012). To ensure

reproducibility, each analysis was carried out in triplicates at least three times. The TS value of the sample is 19.4 (0.12), VS value is 18.7 (0.16), and pH 3.

Research methods of fuzzy approach

Anaerobic digestion is a known technique that has been used for many years to treat waste and thereby obtain renewable energy. As can be understood from the literature, many different types of organic waste can be separated and used as raw materials to produce biogas through the anaerobic digestion process. However, the biodegradability and methane potential of these materials can differ significantly. These situations are important when considering the industrial biogas plant design and the operation and economy of this plant. Therefore, it is very important to analyze raw materials before anaerobic digestion. BMP testing is one such approach and is widely used to analyze feedstock, namely biodegradability and methane potential (Wang et al., 2014). However, there are many parameters that affect the BMP test. For example, some studies in the literature include substrate pretreatment, inoculum source, and digestion temperature (Carlsson et al., 2012; Facchin et al., 2013; Lianhua et al., 2010). But, these are not the only parameters. Fifteen important parameters that are effective in the BMP process are shown in Table 2 below, and the cause-effect mechanism of all these parameters with each other is investigated. In this context, the next section analyses integrated fuzzy sets and DEMATEL approaches for revealing the causal and effect relation of BMP parameters.

Fundamentals of fuzzy logic and fuzzy sets used in BMP

Lotfi A. Zadeh suggested the use of fuzzy logic strategy in situations where there is often inextricable uncertainty and ambiguity in human decisions. Many issues in real life, especially in engineering applications, depend on more than one variable and these variables affect each other in an obscurity (Zadeh, 1996). It is a known fact that linguistic terms can be used to analyze the system by taking the opinions of individuals or groups on a complex technical issue, and then, these terms can be converted into fuzzy numbers and healthy solutions can be obtained. In this way, complex decision-making problems are solved with the help of fuzzy numbers. A triangular fuzzy number (TFN) can be explained as a triplet $\widetilde{A} = (l, m, u)$ where l, m and u denote lower, medium, and upper numbers of the fuzzy which is crisp and real numbers ($x \le y \le z$). The membership function of a TFN can be shown as Eq. (2) below:

$$\mu_{\widetilde{A}} = \begin{cases} 0, & x < l \\ (x-l)/(m-l), & l \le x \le m \\ (u-x)/(u-m), & m \le x \le u \\ 0 & x \ge u \end{cases} \tag{2}$$

Figure 1 contains the representation of a TFN described above. The particulars of the relationship between verbal statements and TFNs are given in Table 1. In addition, fuzzy ratings and membership functions are illustrated in Fig. 2 to understand the system.

For any two randomly chosen TFNs $\widetilde{A}_1 = (l_1, m_1, u_1)$ and $\widetilde{A}_2 = (l_2, m_2, u_2)$, the mathematical calculation of two TFNs can be represented as below:

TFNs between the nested transactions;

The operation of removing triangles among fuzzy numbers;

$$\widetilde{A}_1 + \widetilde{A}_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{3}$$

$$\widetilde{A}_1 - \widetilde{A}_2 = (l_1 - u_2, m_1 - m_2, u_1 - l_2) \tag{4}$$

Multiplication between TFNs;

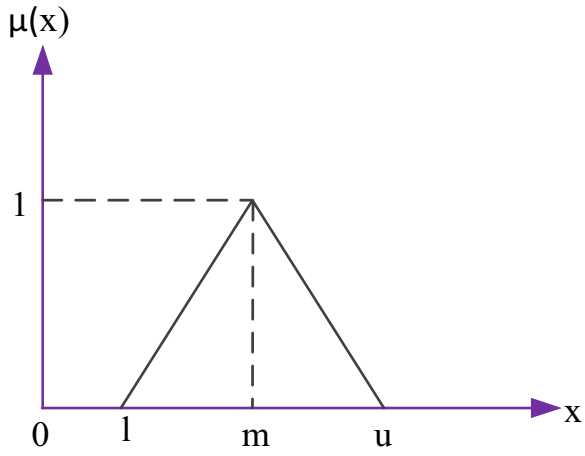


Fig. 1 Triangular fuzzy number (TFN)

Table 1 Linguistic relationship between verbal terms and TFN

Linguistic (verbal) terms	TFN
No influence (No)	(0, 0, 0.25)
Very low influence (VL)	(0, 0.25, 0.5)
Low influence (L)	(0.25, 0.5, 0.75)
High influence (H)	(0.5, 0.75, 1)
Very high influence (VH)	(0.75, 1, 1)

$$\widetilde{A}_1 x \widetilde{A}_2 = \left(l_1 x l_2, m_1 x m_2, u_1 x u_2\right) \tag{5}$$

Arithmetic operation for TFNs;

$$k x \widetilde{A}_1 = \left(k x l_1, k x m_1, k x u_1\right), (k > 0) \tag{6}$$

$$\frac{\widetilde{A}_1}{k} = \left(\frac{l_1}{k}, \frac{m_1}{k}, \frac{u_1}{k}\right), (k > 0) \tag{7}$$

Equation (8) is used to obtain the normalized direct relationship matrix (NDRM). It should be known that all diagonal elements (values) in the matrix must be zero. Furthermore, the total relationship matrix T can be obtained by using Eq. (9). Finally, r_i and c_j are obtained with the help of the Eqs. (10) and (11).

$$D = \frac{1}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} a_{ij}} \tag{8}$$

$$T = D(1 - D)^{-1} \tag{9}$$

$$r_i = \sum_{1 \le j \le n} t_{ij} \tag{10}$$

$$c_j = \sum_{1 \le i \le n} t_{ij} \tag{11}$$

Combination of fuzzy sets and DEMATEL method

Fuzzy sets and DEMATEL methods are used together in order to make an effective and sensitive evaluation. A flowchart of how to use the fuzzy DEMATEL method is shown in Fig. 3. The basic sequences of methods are also shown as follows (Chen-Yi et al., 2007; Liou et al., 2008; Wu & Lee, 2007).

***Step 1: Identify experts*:** It is important to choose experts who have worked on BMP and has sufficient experience. It is critical to obtain meaningful results that they have studied the effects of many parameters affecting BMP.

***Step 2: Identify factors and construct fuzzy scale*:** Experts who have worked on BMP and have profound knowledge on this issue need to determine the most important criteria. This step is very important to understand the cause-effect relationship between problems and/or technical features during the BMP process. Five scales (no effect, very low impact, low impact, high impact, and very high impact) were used due to verbal variables, linguistic terms, and fuzzy numbers for the experts to make an easy assessment. Once these relationships are established, experts carefully evaluate and compare the criteria in pairs. However, when making this comparison, it is difficult to determine to what extent one factor affects another. To overcome this difficulty, fuzzy scale has been proposed. According to this scale, the effect of one

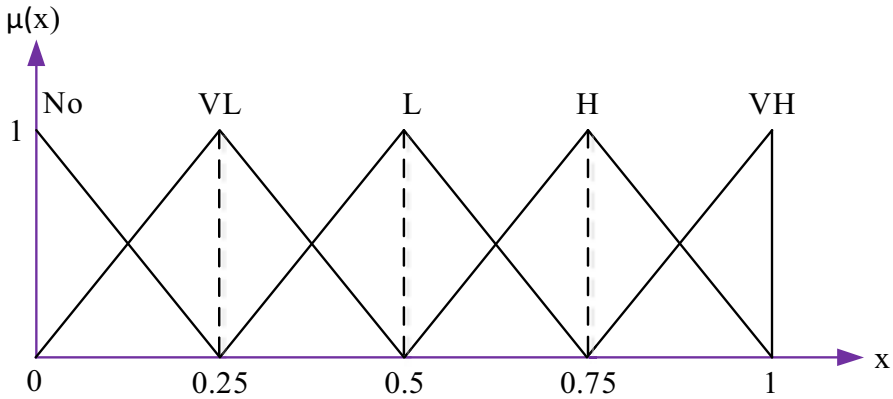


Fig. 2 Fuzzy ratings and their membership function

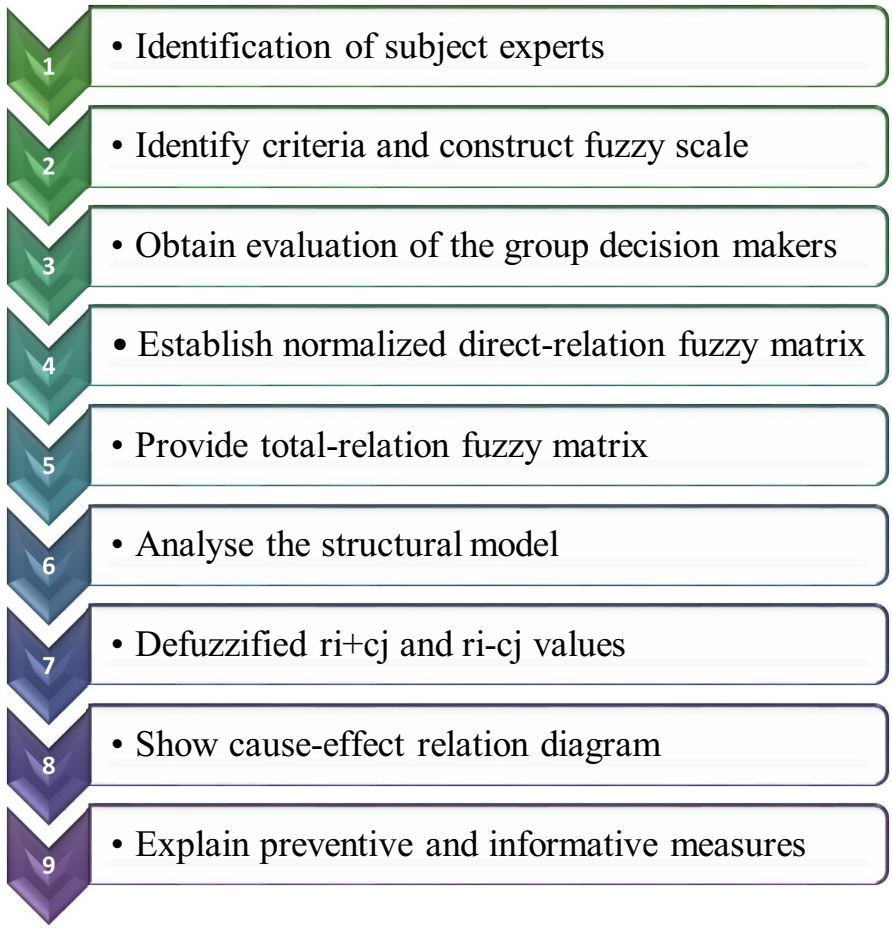


Fig. 3 Flow order of the fuzzy DEMATEL approach (Başhan & Demirel, 2019)

factor on another factor is accepted as a linguistic variable and is expressed in Table 1 above. Then, the relevant TFNs are allocated.

***Step 3: Acquire an evaluation of the experts*:** Comparison between criteria is obtained in terms of verbal variables. In addition, all fuzzy evaluations are defuzzified and aggregated as a crisp value. Finally, the initial direct-relation fuzzy matrix ($\widetilde{E}$) of the BMP experts is obtained.

$$\widetilde{E} = \begin{bmatrix} 0 & \cdots & \widetilde{E}_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{E}_{n1} & \cdots & 0 \end{bmatrix} \tag{12}$$

$$\widetilde{e}_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right) \tag{13}$$

***Step 4: Indicate NDRFM*:** With the help of the first direct relation matrix, the NDRFM is obtained. To ensure that, firstly $\widetilde{\beta}_i$ and γ as are considered as TFN. The following calculation is done sequentially.

$$\widetilde{\beta}_i = \sum \widetilde{e}_{ij} = \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij}\right) \tag{14}$$

$$\gamma = max\left(\sum_{j=1}^{n} u_{ij}\right) \tag{15}$$

Also, linear scale transformation is applied to convert the factors to their corresponding scales. The NDRFM ($\widetilde{F}$) of group decision-makers can be shown as follows.

$$\widetilde{F} = \begin{bmatrix} \widetilde{\widetilde{F}}_{11} & \cdots & \widetilde{F}_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{F}_{n1} & \cdots & \widetilde{F}_{nn} \end{bmatrix} \tag{16}$$

where $\widetilde{f}_{ij} = \frac{\widetilde{e}_{ij}}{\gamma} = \left(\frac{\widetilde{e}_{ij}}{\gamma}, \frac{\widetilde{e}_{ij}}{\gamma}, \frac{\widetilde{e}_{ij}}{\gamma}\right)$

***Step 5: Determine total-relation fuzzy matrix*:** First of all, after the NDRFM is created, making sure that $\lim_{\omega\to\infty} F^{\omega} = 0$ the total relation fuzzy matrix is calculated. Then, the exact state of the total relation fuzzy matrix is determined as follows.

$$\widetilde{T} = \lim_{\omega\to\infty}\left(\widetilde{F} + \widetilde{F}^2 + \cdots + \widetilde{F}^{\omega}\right) \tag{17}$$

$$\widetilde{T} = \begin{bmatrix} \widetilde{t}_{11} & \cdots & \widetilde{t}_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{t}_{n1} & \cdots & \widetilde{t}_{nn} \end{bmatrix} \tag{18}$$

where $\widetilde{t}_{ij=} = (l''_{ij}, m''_{ij}, u''_{ij})$

$$Matrix\left[l''_{ij}\right] = F_l x(I - F_l)^{-1} \tag{19}$$

$$Matrix\left[m''_{ij}\right] = F_m x(I - F_m)^{-1} \tag{20}$$

$$Matrix\left[u''_{ij}\right] = F_u x(I - F_u)^{-1} \tag{21}$$

***Step 6: Evaluation of the fuzzy structural model*:** After calculating matrix $\widetilde{T}$, $\widetilde{r}_i + \widetilde{c}_j$ and $\widetilde{r}_i - \widetilde{c}_j$ are calculated. In the equation, $\widetilde{r}_i$ and $\widetilde{c}_j$ denote the sum of the rows and columns of matrix $\widetilde{T}$. While $\widetilde{r}_i + \widetilde{c}_j$ shows the significance of factor i, $\widetilde{r}_i - \widetilde{c}_j$ indicates the net effect of factor i.

***Step 7: Defuzzify $\widetilde{r}_i + \widetilde{c}_j$ and $\widetilde{r}_i - \widetilde{c}_j$*:** Since then, $\widetilde{r}_i + \widetilde{c}_j +$ and $\widetilde{r}_i - \widetilde{c}_j$ are defuzzified by using the COA (center of area) defuzzification method which is created by Ross (2009) for determining BNP (best non-fuzzy performance) value. For a convex fuzzy number $\widetilde{\delta}$, a real number z^* corresponding to its center of area can be shown as below (Gumus et al., 2013).

$$z^* = \frac{\int \mu_{\widetilde{\delta}}(z) z dz}{\int \mu_{\widetilde{\delta}}(z) dz} \tag{22}$$

The BNP value of a fuzzy number $\widetilde{G} = \left(l_{ij}, m_{ij}, u_{ij}\right)$ can be calculated with below formula.

$$BNP_{ij} = \frac{u_{ij} - l_{ij} + m_{ij} - l_{ij}}{3} + l_{ij} \tag{23}$$

***Step 8: Show cause-effect relation diagram*:** As a result of these processes, the $r_i + c_j$ and $r_i - c_j$ data sets are represented, and a diagram of the cause-effect relationship (cause above the origin and effect below the y-axis) is created. The calculation can be done with step 6.

***Step 9: Explain importance of parameters*:** It should be briefly stated why among the parameters that have the highest priority in terms of cause-effect, their effects on the system are higher.

Using the fuzzy DEMATEL method in BMP problems

This part contains the fuzzy DEMATEL method applied to assess the most effective parameters for biochemical methane potential. The relationships of 15 critical components determined by a general evaluation are discussed.

Important parameters of BMP and system description

Common important parameters of BMP are listed in Table 2 below. Also, a simple schematic diagram of the BMP system is shown in Fig. 4. Considering the details of these parameters in the sub-fractions, important parameters in the BMP system were determined.

Application of the Fuzzy DEMATEL method on the BMP

The vital parameters affecting the BMP system are provided in Table 2 and the above detailed environmental engineers (academicians) were asked to analyze the relationship between these 15 important process parameters, to compare and analyze the parameters pairwise. These academics are in the department of environmental engineering and they are full-time professors, each with at least 20 years of experience. Afterward, the average of the opinions of these three experts was obtained according to the principles of the fuzzy DEMATEL method. Three experts separately agreed on the results. Environmental engineers experienced at BMP evaluated the relationship between 15 technical components identified using a fuzzy verbal scale. The obtained direct fuzzy matrix is shown in Table 4. Afterward,

Table 2 The most vital parameters of BMP

Code	Parameters
C1	Temperature
C2	pH
C3	Type of organic matter
C4	Hydraulic dwell time
C5	C/N ratio
C6	Toxins
C7	Total solid amount (TSA)
C8	Volatile matter concentration (kg/m^3)
C9	The effect of mixing
C10	Type of graft mud
C11	Effect of pressure
C12	Particle size
C13	Reactor volume and dimensions
C14	Reactor material
C15	The heating system and insulation properties

an NDRFM was obtained with the help of Eqs. (14)–(16). The results of the NDRFM are shown in Table 5. To obtain the total relation fuzzy matrix, Eqs. (17)–(21) are used. Besides, Table 6 shows the total-relation fuzzy matrix. Lastly, Table 7 shows defuzzified threshold values of T-matrix and also fuzzy values of $\widetilde{r}_i, \widetilde{c}_j$, $\widetilde{r}_i + \widetilde{c}_j$, and $\widetilde{r}_i - \widetilde{c}_j$ are shown in Table 8 and finally in the presence of above, by using Eqs. (22) and (23), the crisp values have been obtained and given in Table 9.

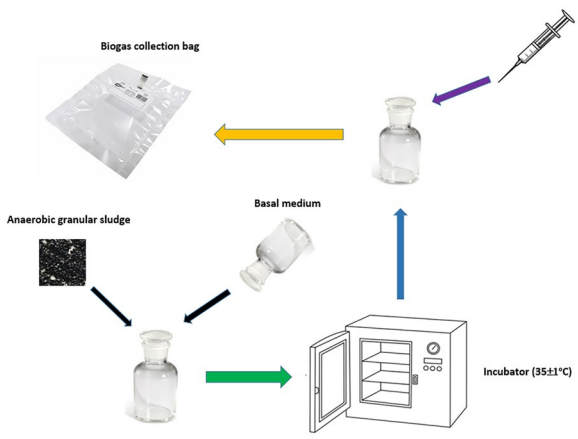


Fig. 4 Schematic diagram of experimental BMP analysis

Results and discussion

Biogas yield

In Table 3, the results of the average daily biogas yield and the average cumulative biogas yield measured from VW are shared.

The average cumulative biogas yield of the reactor is 282.1 NmL/g VS. It was seen that biogas production decreased with time. The highest percentage of methane formed in the biogas occurred on the 21st day. This low methane yield is most likely due to the conversion of organic matter to intermediates such as VFA (Ünyay et al., 2022).

Findings and interpretations of the BMP parameters relations

The DEMATEL method aims at solving complex problems. This method has been developed in order to understand and develop the solution logic of multi-parameter problems or systems, and to define applicable solutions according to the effect of problem groups or system parameters. The DEMATEL method provides the basis of graph theory and divides the factors that provide a clear understanding of the causal relationship as cause and effect. The method examines the structure, relationships, and alternatives between components. It includes a conciliatory cause-effect model. It deals with indirect interactions. The criteria are in order of priority according to the types of relations and the degrxee of importance of the effects they have on each other. Cause criteria are

Table 3 Average cumulative biogas yield and methane contents of reactors

Time (days)	Cumulative biogas yield (NmL/g VS)	Methane (%)
7	235.0 (22.0)	75.521 (1.3)
14	256.0 (21.0)	77.842 (1.5)
21	312.0 (23.0)	79.230 (1.6)
32	325.4 (19.0)	76.412 (1.3)

Table 4 The initial direct-relation fuzzy matrix

	C1	C2	C3	C4	…	C12	C13	C14	C15
C1	(0, 0, 0.25)	(0.75, 1, 1)	(0, 0, 0.25)	(0, 0, 0.25)	…	(0.25, 0.50, 0.75)	(0, 0, 0.25)	(0, 0, 0.25)	(0.75, 1, 1)
C2	(0.50, 0.75, 1)	(0, 0, 0.25)	(0, 0.25, 0.50)	(0, 0, 0.25)	…	(0.17, 0.42, 0.67)	(0, 0, 0.25)	(0, 0, 0.25)	(0.75, 1, 1)
C3	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	…	(0.75, 1, 1)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)
C4	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	…	(0, 0, 0.25)	(0.25, 0.50, 0.75)	(0, 0, 0.25)	(0, 0, 0.25)
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
C12	(0.42, 0.67, 0.92)	(0.58, 0.83, 1)	(0.75, 1, 1)	(0.50, 0.75, 0.92)	…	(0, 0, 0.25)	(0.75, 1, 1)	(0, 0, 0.25)	(0, 0.17, 0.42)
C13	(0.75, 1, 1)	(0.50, 0.75, 1)	(0, 0, 0.25)	(0.75, 1, 1)	…	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0.25, 0.50, 0.75)
C14	(0.75, 1, 1)	(0.75, 1, 1)	(0, 0, 0.25)	(0, 0, 0.25)	…	(0, 0, 0.25)	(0.67, 0.92, 1)	(0, 0, 0.25)	(0, 0, 0.25)
C15	(0.75, 1, 1)	(0.75, 1, 1)	(0, 0, 0.25)	(0, 0.25, 0.50)	…	(0, 0, 0.25)	(0.75, 1, 1)	(0, 0, 0.25)	(0, 0, 0.25)

criteria that affect other criteria more and have high priority. Effect criteria are those that are more influenced by other criteria and have relatively second-order priority. In a fuzzy environment, this method is applied in solving complex problems involving causal relationships. It analyses the strength of dependencies and relationships between factors with the matrix method and mathematical techniques.

The fuzzy DEMATEL method is an extensive approach for constructing and analyzing a structural model that encompasses causal relationships between multi criteria complex factors. The 15 criteria of BMP are divided into two groups as the cause group and the effect group. Finding out which factors affect and which are affected is an important step in solving the complex problems under consideration. Therefore, the DEMATEL is a method used to determine the cause and effect factors, which have a complex structure in developing technical parameters relations (Tables 4, 5, 6, 7, 8, and 9).

Table 5 Normalized initial direct-relation fuzzy matrix

	C1	C2	C3	C4	…	C12	C13	C14	C15
C1	(0, 0, 0.02)	(0.07, 0.09, 0.09)	(0, 0, 0.02)	(0, 0, 0.02)	…	(0.02, 0.04, 0.07)	(0, 0, 0.02)	(0, 0, 0.02)	(0.07, 0.09, 0.09)
C2	(0.04, 0.07, 0.09)	(0, 0, 0.02)	(0, 0.02, 0.04)	(0, 0, 0.02)	…	(0.01, 0.04, 0.06)	(0, 0, 0.02)	(0, 0, 0.02)	(0.07, 0.09, 0.09)
C3	(0, 0, 0.02)	(0, 0, 0.02)	(0, 0, 0.02)	(0, 0, 0.02)	…	(0.07, 0.09, 0.09)	(0, 0, 0.02)	(0, 0, 0.02)	(0, 0, 0.02)
C4	(0, 0, 0.02)	(0, 0, 0.02)	(0, 0, 0.02)	(0, 0, 0.02)	…	(0, 0, 0.02)	(0.02, 0.04, 0.07)	(0, 0, 0.02)	(0, 0, 0.02)
⋮	⋮	⋮	(0, 0.02, 0.04)	⋮	⋮	⋮	⋮	⋮	⋮
C12	(0.04, 0.06, 0.08)	(0.05, 0.07, 0.09)	(0.07, 0.09, 0.09)	(0.04, 0.07, 0.08)	…	(0, 0, 0.02)	(0.07, 0.09, 0.09)	(0, 0, 0.02)	(0, 0.01, 0.04)
C13	(0.07, 0.09, 0.09)	(0.04, 0.07, 0.09)	(0, 0, 0.02)	(0.07, 0.09, 0.09)	…	(0, 0, 0.02)	(0, 0, 0.02)	(0, 0, 0.02)	(0.02, 0.04, 0.07)
C14	(0.07, 0.09, 0.09)	(0.07, 0.09, 0.09)	(0, 0, 0.02)	(0, 0, 0.02)	…	(0, 0, 0.02)	(0.06, 0.08, 0.09)	(0, 0, 0.02)	(0.01, 0.04, 0.06)
C15	(0.07, 0.09, 0.09)	(0.07, 0.09, 0.09)	(0, 0, 0.02)	(0, 0.02, 0.04)	…	(0, 0, 0.02)	(0.07, 0.09, 0.09)	(0, 0, 0.02)	(0, 0, 0.02)

Table 6 Total-relation fuzzy matrix

	C1	C2	C3	C4	…	C12	C13	C14	C15
C1	(0.01, 0.04, 0.19)	(0.08, 0.14, 0.27)	(0.01, 0.04, 0.16)	(0.01, 0.03, 0.18)	…	(0.03, 0.07, 0.20)	(0.01, 0.03, 0.14)	(0, 0.01, 0.10)	(0.07, 0.11, 0.21)
C2	(0.06, 0.11, 0.27)	(0.02, 0.05, 0.23)	(0.01, 0.06, 0.19)	(0.01, 0.04, 0.19)	…	(0.02, 0.07, 0.20)	(0.01, 0.03, 0.15)	(0, 0.01, 0.11)	(0.07, 0.11, 0.22)
C3	(0.01, 0.03, 0.18)	(0.01, 0.04, 0.20)	(0.02, 0.05, 0.17)	(0.02, 0.05, 0.18)	…	(0.08, 0.12, 0.22)	(0.01, 0.02, 0.13)	(0, 0.01, 0.10)	(0, 0.02, 0.14)
C4	(0.01, 0.03, 0.17)	(0.01, 0.03, 0.19)	(0.01, 0.03, 0.15)	(0.01, 0.04, 0.17)	…	(0.01, 0.02, 0.14)	(0.02, 0.05, 0.17)	(0, 0.01, 0.10)	(0, 0.01, 0.13)
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
C12	(0.05, 0.10, 0.26)	(0.06, 0.12, 0.29)	(0.07, 0.12, 0.24)	(0.06, 0.11, 0.25)	…	(0.01, 0.04, 0.18)	(0.07, 0.11, 0.22)	(0, 0.01, 0.11)	(0.01, 0.04, 0.18)
C13	(0.07, 0.11, 0.22)	(0.05, 0.09, 0.23)	(0, 0.01, 0.13)	(0.07, 0.10, 0.20)	…	(0, 0.02, 0.13)	(0, 0.1, 0.11)	(0, 0, 0.08)	(0.03, 0.06, 0.16)
C14	(0.08, 0.12, 0.23)	(0.08, 0.12, 0.24)	(0.01, 0.02, 0.14)	(0.01, 0.02, 0.15)	…	(0.01, 0.02, 0.13)	(0.06, 0.09, 0.19)	(0, 0.01, 0.09)	(0.03, 0.07, 0.17)
C15	(0.08, 0.11, 0.22)	(0.08, 0.12, 0.23)	(0, 0.01, 0.13)	(0.01, 0.04, 0.17)	…	(0, 0.02, 0.13)	(0.07, 0.10, 0.18)	(0, 0, 0.09)	(0.01, 0.03, 0.13)

Cause factors

Biogas is produced through a biochemical process, which is affected by several parameters including substrate type, particle size, temperature range, pH, carbon/nitrogen (C/N) ratio, and graft concentration. In addition, smaller feedstock generally increases its biodegradability and therefore the rate of biogas production, while larger particles can clog the digester system. When systems are fed continuously, the residue of the digestion product is discharged at the same rate, resulting in a steady-state and gas production rate. Therefore, continuously fed systems directly affect biogas production. In the BMP process, the tools and equipment used, the technical parameters, and the way they are used have a significant impact on the result. For this reason, 15 technical parameters determined in this study were examined and divided into two groups as cause-effect factors. The first four cause factors are C14 (the material from which the

Table 7 Defuzzified threshold values of T-matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1	0.08	0.16	0.07	0.07	0.11	0.17	0.07	0.08	0.07	0.09	0.13	0.1	0.06	0.04	0.06
C2	0.14	0.1	0.09	0.08	0.12	0.17	0.09	0.1	0.09	0.11	0.11	0.1	0.06	0.04	0.06
C3	0.08	0.09	0.08	0.08	0.14	0.16	0.14	0.13	0.05	0.08	0.09	0.14	0.05	0.04	0.04
C4	0.07	0.08	0.07	0.07	0.13	0.14	0.12	0.11	0.06	0.08	0.05	0.06	0.08	0.04	0.04
C5	0.14	0.13	0.15	0.15	0.1	0.17	0.12	0.14	0.05	0.14	0.07	0.1	0.06	0.04	0.04
C6	0.11	0.17	0.17	0.15	0.18	0.14	0.13	0.17	0.09	0.16	0.13	0.15	0.12	0.11	0.1
C7	0.09	0.12	0.15	0.15	0.16	0.15	0.08	0.12	0.07	0.12	0.06	0.12	0.06	0.04	0.04
C8	0.1	0.13	0.14	0.15	0.15	0.14	0.11	0.08	0.05	0.12	0.06	0.07	0.05	0.04	0.04
C9	0.1	0.12	0.06	0.13	0.07	0.16	0.06	0.06	0.05	0.11	0.07	0.07	0.05	0.04	0.04
C10	0.07	0.06	0.05	0.05	0.13	0.1	0.05	0.09	0.03	0.05	0.04	0.04	0.04	0.03	0.03
C11	0.11	0.13	0.04	0.05	0.05	0.1	0.04	0.05	0.04	0.05	0.05	0.05	0.04	0.03	0.03
C12	0.14	0.16	0.14	0.14	0.1	0.15	0.13	0.08	0.08	0.14	0.07	0.07	0.13	0.04	0.04
C13	0.13	0.12	0.05	0.12	0.08	0.08	0.05	0.05	0.04	0.05	0.05	0.05	0.04	0.03	0.04
C14	0.14	0.15	0.05	0.06	0.07	0.14	0.05	0.06	0.04	0.06	0.06	0.05	0.11	0.03	0.04
C15	0.14	0.14	0.05	0.07	0.06	0.1	0.05	0.05	0.06	0.06	0.05	0.05	0.11	0.03	0.03

Table 8 Fuzzy values of $\widetilde{r}_i, \widetilde{c}_j, \widetilde{r}_i + \widetilde{c}_j, \widetilde{r}_i - \widetilde{c}_j$

	$\widetilde{r}_i$	$\widetilde{c}_j$	$\widetilde{r}_i + \widetilde{c}_j$	$\widetilde{r}_i - \widetilde{c}_j$
C1	(0.12, 0.32, 1.91)	(0.25, 0.57, 2.46)	(0.38, 0.88, 4.37)	(−2.34, −0.25, 1.65)
C2	(0.15, 0.47, 2.29)	(0.44, 0.99, 3.34)	(0.59, 1.46, 5.62)	(−3.18, −0.53, 1.85)
C3	(0.46, 0.85, 2.89)	(0.29, 0.69, 2.73)	(0.75, 1.54, 5.63)	(−2.28, 0.16, 2.60)
C4	(0, 0.10, 1.53)	(0.31, 0.80, 2.97)	(0.31, 0.90, 4.50)	(−2.97, −0.70, 1.23)
C5	(0.22, 0.56, 2.43)	(0.28, 0.71, 2.77)	(0.49, 1.27, 5.19)	(−2.55, −0.16, 2.15)
C6	(0.19, 0.52, 2.34)	(0.08, 0.32, 2.02)	(0.27, 0.84, 4.36)	(−1.83, 0.20, 2.26)
C7	(0.24, 0.58, 2.58)	(0.31, 0.72, 2.80)	(0.55, 1.30, 5.38)	(−2.55, −0.14, 2.27)
C8	(0.40, 0.95, 3.22)	(0.37, 0.73, 2.74)	(0.77, 1.68, 5.95)	(−2.34, 0.22, 2.84)
C9	(0.44, 1.09, 3.60)	(0.15, 0.43, 2.18)	(0.59, 1.52, 5.78)	(−1.75, 0.66, 3.45)
C10	(0.31, 0.72, 2.85)	(0.17, 0.48, 2.27)	(0.49, 1.20, 5.12)	(−1.95, 0.24, 2.68)
C11	(0.30, 0.71, 2.76)	(0.09, 0.33, 2.04)	(0.39, 1.04, 4.80)	(−1.74, 0.38, 2.66)
C12	(0.38, 0.90, 3.17)	(0.13, 0.36, 2.07)	(0.51, 1.26, 5.24)	(−1.68, 0.55, 3.04)
C13	(0.04, 0.21, 1.79)	(0.20, 0.48, 2.23)	(0.23, 0.69, 4.02)	(−2.19, −0.26, 1.59)
C14	(0.04, 0.21, 1.78)	(0.47, 0.93, 3.09)	(0.51, 1.14, 4.87)	(−3.04, −0.72, 1.31)
C15	(0.78, 1.51, 4.23)	(0.54, 1.15, 3.64)	(1.31, 2.66, 7.86)	(−2.86, 0.36, 3.69)

reactor is made) with the highest r_i-c_j value of 0.55, C12 (particle size) with the 0.43 value of r_i-c_j, C9 (the effect of mixing) with the r_i-c_j value of 0.32, and C7 (total solids amount (TSA)) with the r_i-c_j value of 0.25 in order of importance, as can be seen in Fig. 5.

Effect factors

The optimum pH in biogas production is usually in the range of 7–8.5. In anaerobic production processes, the growth rate of microorganisms, product production rate, and nutrient consumption rate are seriously affected by temperature. Therefore, the temperature parameter is important for anaerobic systems. In order to obtain maximum biogas efficiency and methane production efficiency from anaerobic processes, the system must have the optimum temperature at which microorganisms can live. These processes can operate under mesophilic and thermophilic conditions, but they are generally operated under mesophilic conditions. The optimum system temperature is usually 30–40 °C for mesophilic microorganisms and 55–60 °C for thermophilic microorganisms. One of the parameters affecting BMP efficiency is carbon and nitrogen concentration. In order for biogas production to take place, the input substrate C/N ratio in the system is important. The carbon source in the used substrate is carbohydrates, and the nitrogen source is protein, nitrate, and ammonia. Bacteria use carbon for energy production and use nitrogen for new cell synthesis. The C/N ratio in the substrate entering the system should be approximately between 20:1 and 30:1. Carbon consumption is 25–30 times higher than nitrogen. When the 15 effective parameters in the BMP process were examined, the fuzzy DEMATEL method divided these parameters into two groups the cause and the effect. In the effect group, C2 (pH), C5 (C/N ratio), and C1 (temperature) were the three most effective parameters, respectively. When Fig. 5 is examined, it will be seen that C2 has

Table 9 Crisp values of $\widetilde{r}_i, \widetilde{c}_j, \widetilde{r}_i + \widetilde{c}_j, \widetilde{r}_i - \widetilde{c}_j$

	$\widetilde{r}_i$	$\widetilde{c}_j$	$\widetilde{r}_i + \widetilde{c}_j$	$\widetilde{r}_i - \widetilde{c}_j$
C1	1.43	1.64	3.07	−0.20
C2	1.55	1.86	3.41	−0.31
C3	1.40	1.35	2.75	0.04
C4	1.20	1.54	2.74	−0.34
C5	1.61	1.65	3.26	−0.05
C6	2.10	2.06	4.16	0.04
C7	1.55	1.29	2.84	0.25
C8	1.43	1.37	2.80	0.06
C9	1.19	0.88	2.07	0.32
C10	0.86	1.41	2.27	−0.55
C11	0.87	1.07	1.94	−0.20
C12	1.64	1.21	2.85	0.43
C13	1.05	1.07	2.12	−0.03
C14	1.17	0.61	1.78	0.55
C15	1.09	1.11	2.19	−0.02

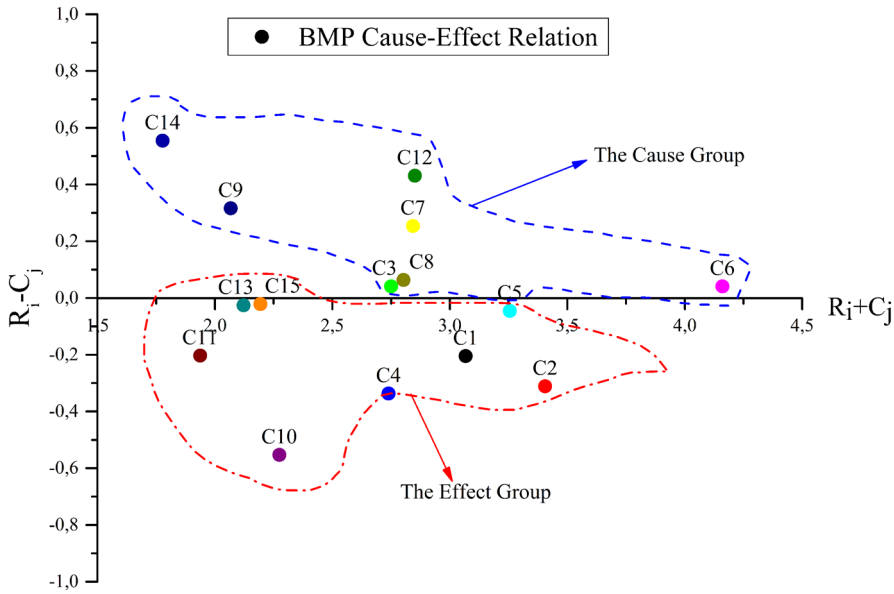


Fig. 5 The cause-effect relation diagram of BMP parameters

the highest Ri + Cj value of (3.41). C5 has a Ri + Cj value of 3.26. The Ri + Cj value of C1 was calculated as 3.07. The points to be considered regarding all these parameters are stated in the section below.

Recommendations for important BMP parameters

BMP tests are commonly used to determine the methane potential of substrates. BMP test results depend on many variables. Some of the most important factors for BMP testing are concentration, temperature, pH, C/N ratio, and source. It has been observed that the level of inoculum concentration affects the rate and rate of biodegradation. The higher the inoculum concentration, the faster the anaerobic conversion of the substrate occurs. Different inoculum sources may have different rates of biodegradability due to different microbial populations and levels of diversity. If the substrate is homogeneous, the potential to produce methane in the reactor increases. It is very important that the ambient conditions in methane production are mesophilic or thermophilic. High methane yield is seen in mesophilic conditions.

Conclusion

With anaerobic digestion, environmental indirect benefits such as the production of renewable energy and thus the reduction of greenhouse gas emissions to some extent are achieved. As it is well-known from the literature, the methane production potential of the desired substance can be estimated realistically most of the time with BMP. The BMP test provides important information in the design of anaerobic reactors and in planning the optimal conditions for anaerobic degradation. In the result of this study, high methane yield is seen in mesophilic conditions. The average cumulative biogas yield of the reactor is 282.1 NmL/g VS. The highest percentage of methane formed in the biogas occurred on the 21st day. Considering the BMP process as a whole, it is known that many important parameters are important in this process sequence. In this study, 15 important parameters directly related to BMP were determined. In experimental processes, some parameters may affect other parameters. Besides, some parameters can also cause or affect some results when the system as a whole is evaluated. In this context, the fuzzy DEMATEL approach, which is widely used in the literature but has not been applied to the subject of BMP, was used. This method divided 15 important parameters of BMP into two groups the cause and the effect, weighted each parameter based on expert opinions, and ranked them in order of importance. It has been understood that the material of the reactor (r_i-c_j value of 0.55), particle size (r_i-c_j value of 0.43), the effect of mixing (r_i-c_j value of 0.32), and TSA (r_i-c_j value of 0.25), which are in the causal parameters group is the most important causal parameters, respectively. Likewise, pH ($r_i + c_j$ value of 3.41), C/N ratio

($r_i + c_j$ value of 3.26), and temperature ($r_i + c_j$ value of 3.07) in the group of effect parameters were found to be the most important effect parameters, respectively. This study contributes to the literature as the first fuzzy DEMATEL approach applied to the BMP parameters and provides useful information about relations between BMP parameters to researchers.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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