

Article

Analysis Phase of Lean Six Sigma Methodology with Scaled-Down Laboratory Experiments for an Industrial-Scale Biogas Plant

Samet Cinar *, Senem Önen Cinar , She Ming Ng and Kerstin Kuchta

Circular Resource Engineering, Economy and Management, Hamburg University of Technology, Blohmstr. 15, 21079 Hamburg, Germany; senem.oenen@tuhh.de (S.Ö.C.); she.ng@tuhh.de (S.M.N.); kuchta@tuhh.de (K.K.)

* Correspondence: samet.cinar@tuhh.de

Abstract: Although the benefits of the Lean Six Sigma (LSS) methodology have been proven for more than 20 years, it is still underutilized in environmental science, (e.g., in anaerobic digestion and biogas production). In order to obtain a structural and data-oriented perspective for process optimization in the renewable energy sector, LSS application must be considered one of the most valuable tools. To inform this paper, the LSS analysis phase was conducted in a scaled-down environment through detailed laboratory experiments. Results showed not only the feasibility of LSS application in biogas technology, but also some useful findings such as possible root causes for low production, such as impurities, waiting time, and existing pre-treatment methods for the defined problem. The results of the experiments show that the use of old substrates can reduce the biogas production up to half of the production with fresh substrates, and that even a 10% sand content can reduce the production up to 14.2%, which shows the need for a solution to these two issues.

Keywords: lean six sigma; anaerobic digestion; process optimization



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1. Introduction

As has been more recognized day by day, human-caused global warming and climate change over the years are pushing the world toward an apocalyptic scenario. For years, many gatherings have been held and agreements reached about environmental sustainability and measurements against global warming. For this reason, Germany has decided to focus on renewable energy in an effort to reduce greenhouse gas emissions and liaise with the Paris Agreement [1,2].

One of the measures taken against climate change is a focus on renewable energy such as solar power, wind power, and biogas. Biogas plants have made a considerable contribution toward this aim [1,3]. Due to the increasing importance of renewable energy sources, numerous studies have been conducted to optimize biogas plants' operations. Nevertheless, Lean Six Sigma (LSS) Methodology has never been utilized as a structural and statistical approach for process optimization in biogas plants and anaerobic digestion.

Anaerobic Digestion (AD) is a complex biochemical process that degrades organic materials into biomass and biogas with the help of anaerobic bacteria in an oxygen-free environment. This degradation occurs sequentially through hydrolysis to convert complex organic materials into amino acids, sugar, and fatty acids. The next stages of anaerobic digestion include:

- (1) Acidogenesis, where the bacteria transform the previous outputs to lower fatty acids.
- (2) Acetogenesis, which transforms lower fatty acids into acetic acid, hydrogen, and carbon dioxide.
- (3) Methanogenesis, where the biogas methane and carbon dioxide are produced [3–5].

Since anaerobic digestion happens through complex biochemical reactions, operational process parameters are of utmost importance. For example, the organic loading rate (OLR),

hydraulic retention time (HRT), mixing, and pH are some key operational parameters for a biogas production process. Nsair et al., reviewed the operational parameters for biogas technology in 2020, and in particular, the importance and effect of temperature and mixing have recently been intensively studied in order to simulate the best operating conditions for a biogas plant [6–8].

Several studies have also been carried out in different types of operational environments around other operational parameters such as the total organic carbon (TOC), total nitrogen, particle size, total solids, characteristics of feeding, HRT, OLR, and pH. As mentioned above, the studies aimed to define the best individual conditions for biogas production and directly-related anaerobic digestion [9–12].

Last but not least, some modern statistical approaches such as machine learning and predictive analytics have been used to define and predict a better combination of operational parameters in several different scales of biogas production [13–15].

For this article, laboratory experiments were studied to be able to simulate biogas plant operation for implementation of the ‘analyze’ phase of the Define–Measure–Analyze–Improve–Control (DMAIC) cycle of Lean Six Sigma (LSS) methodology. In this study, the feasibility and a possible way to apply the Lean Six Sigma methodology in a large-scale biogas plant were demonstrated using laboratory analysis. Not only the results of this study, but also the way of working can be considered as a guideline in any process optimization project in biogas plants. Since it is not always possible to simulate different scenarios for different parameters in a large-scale biogas plant, simulation of different operational and environmental parameters in a scaled-down laboratory environment is proposed.

2. Materials and Methods

Lean Six Sigma’s analyze phase aims to assess data collected from a biogas plant to determine possible causes of low efficiency and their impacts. The Lean Six Sigma method can be carried out according to the DMAIC cycle (Define–Measure–Analyze–Improve–Control). In the Define phase, the problem, the goal, the stakeholders, the project scope, and the schedule are defined. In the Measure phase, the problem is quantified and Key Performance Indicators (KPIs) are identified. In the Analyze phase, which is also the focus of this article, the root cause of the problem is identified. Solution ideas are defined for the identified cause (s) in the Improve phase, and the Control phase ensures that the achieved level of the process is maintained and the gains are sustained.

An Ishikawa Diagram is used in the beginning of the Analyze phase to determine reasons for lower-than-expected biogas production in the plant. Daily biogas generation by the studied biogas plant was approximately 20% lower than the planned capacity in 2020. This study’s experimental design is based on the following root causes for the low biogas production:

- (1) Loss of possible substrates (which have particle sizes of 60–120 mm and >120 mm) to the composting process rather than anaerobic digestion.
- (2) Addition of the composting leachate, which has an acidic content, to the process.
- (3) High sand content of biowaste fed into the system.
- (4) Long storage time of the substrate, causing degradation.
- (5) Longer hydraulic retention time (HRT).

This section will explain the analysis for each of the above-mentioned causes. The experimental setup and materials are prepared based on the German Standard VDI 4630 for performing a biomethane potential test (BMP). Performed BMP analyses are summarized in the Table below (see Table 1).

Table 1. Summary of BMP test experimental design parameters.

Analyze	Content
Substrate waiting time	Fresh (freshly arrived)
	Old (waited in the arrival area approximately 14 days) Substrate storage (just before feeding into reactor)
Substrate stream	Substrate size <60 mm
	Substrate size 60–120 mm
	Substrate size >120 mm
Sand content of the substrate	Substrate does not contain sand
	Substrate contains 10% sand
	Substrate contains 20% sand
	Substrate contains 40% sand
Addition amount of leachate to the system	No leachate addition
	2.3 mL leachate addition to the lab-scale reactors
	4.5 mL leachate addition to the lab-scale reactors

In addition to the BMP test, total solids (TS), volatile solids (VS), and pH analyses were conducted for the substrate, digestate, and test samples. Furthermore, the sand contents of the different substrate streams were determined in this study's scope to design an experiment for the impact of the sand content in biomethane production efficiency. Substrate and digestate samples were collected from the industrial-scale biogas plant, and homogeneous mixtures were provided. As an inoculum, digestate samples were used. All analyses were performed in three parallels. The temperature of the tests (55 °C) was determined based on the operation temperature of the reference biogas plant. The test duration alternated between 33 to 37 days, based on the produced biomethane amount in the test period's last days.

2.1. BMP Test Design

In the BMP tests, two different systems were used: AMPTS II and a climate-controlled room with a eudiometer. The details were explained in the study performed by Onen Cinar (2021) [16]. Half-liter glass reactors were used for all analyses, and daily hand mixing was implemented in the reactors. In each section, approximate amounts are listed for the mixtures mentioned. Nevertheless, exact weight information was used for the calculations for each reactor. In the tests performed with the eudiometer, the biogas content was determined regularly by using gas chromatography (GC). In general, inoculum–digestate mixing amounts were determined based on the following equation (Equation (1)) [17]:

$$\frac{VS_{Substrate}}{VS_{Inoculum}} \leq 0.5 \quad (1)$$

2.2. Determination of the TS Content

Samples were weighed in crucibles as wet samples before putting them in a 105 °C oven. After constant weight was achieved at 105 °C, samples were kept first in a desiccator to reach room temperature and then weighed. The TS content was calculated as in Equation (2), where W_1 is the weight of the empty crucible and the dried sample, W_2 is the weight of the empty crucible, and W_3 is the weight of the empty crucible and the wet sample [18].

$$\%TS = \frac{W_1 - W_2}{W_3 - W_2} \times 100 \quad (2)$$

2.3. Determination of the VS Content

After the TS analysis, the VS analysis was performed with the same crucibles, using a muffle oven over five hours to burn down all of the sample's organic content. Equation (3),

where W_4 is the weight of the empty crucible and the residue after ignition, was used for the calculation of the VS content in TS [19].

$$\%VS = \frac{W_1 - W_4}{W_1 - W_2} \times 100 \quad (3)$$

2.4. Analyzing the Impact of the Substrate Waiting Time on the Biomethane Production Efficiency

In order to determine the impact of the substrate waiting time on the biomethane production efficiency, a BMP test was performed by implementing five different scenarios:

- (1) Blank (digestate),
- (2) Fresh biomass + digestate,
- (3) Old biowaste + digestate,
- (4) Biowaste from mixer + digestate,
- (5) Reference + digestate.

A reference set was performed to evaluate the inoculum's performance, for which cellulose was chosen as a substrate. Approximately 170 g of digestate and 20 g of substrate were added to the reactors. A reference sample was prepared by mixing approximately 2.5 g of Cellulose (Avicel® PH-101, 50 µm) and 170 g of digestate. To supply a homogeneous mixture in the reactor, materials were mixed carefully before starting the test. A pH measurement was performed in each bottle before and after the test. Before connecting bottles to the AMPTS II system, a one-minute nitrogen flush was conducted to supply anaerobic conditions. During the analysis, reactors were kept in the water bath at 55 °C. Biomethane generation data were recorded automatically in AMPTS II software.

2.5. Assessment of the Impact on the Input Stream on the Biomethane Production Efficiency

The studied biogas plant consists of a composting plant and a biogas plant. To separate input streams between these plants, sorting was implemented based on the size of the materials. This method separates the waste into three different streams:

- (1) Smaller than 60 mm,
- (2) Between 60 mm and 120 mm,
- (3) Larger than 120 mm.

The aim of this analysis was to determine how much biogas potential is lost to the composting stream. To determine this amount, a BMP test was implemented with each fraction as well as the reference sample. The same amounts were implemented and the same procedure conducted with these samples as in Section 2.4.

2.6. Determination of the Substrate's Sand Content's Effect on the Biomethane Generation Efficiency

Unlike the other analyses, in this section, different waste streams' sand content was determined first. Afterwards, experiments were performed with different scenarios to evaluate the feasibility of sand pre-treatment.

2.6.1. Determination of the Sand Content in the Biowaste

No adequate method for determining impurities in wet biowaste has been in practice. Due to the fibrous components of the biowaste, performing an analysis with wet samples is very difficult and time consuming. The method used in this study was improvised from the study conducted by Jank et al., (2016). The sand content was classified as:

- (1) >2 mm gravel,
- (2) 0.63–2 mm sand,
- (3) 0.1–0.63 mm fine sand,
- (4) 0.06–0.1 mm very fine sand [5,20–22].

The sand content of all substrate streams at the biogas plant was determined. The streams were:

- (1) >120 mm biowaste fraction,
- (2) 60–120 mm biowaste fraction,
- (3) <60 mm biowaste fraction,
- (4) Fresh biowaste,
- (5) Old biowaste,
- (6) Substrate from substrate storage.

First, the substrate samples from all of those fractions were dried at 105 °C. Dried samples were analyzed in a vibratory sieve shaker (Retsch, AS 300) as represented in Figure 1. The implemented settings were:

- (1) 0.5 mm g-1 amplitude,
- (2) 10-min duration,
- (3) 10-s interval time.

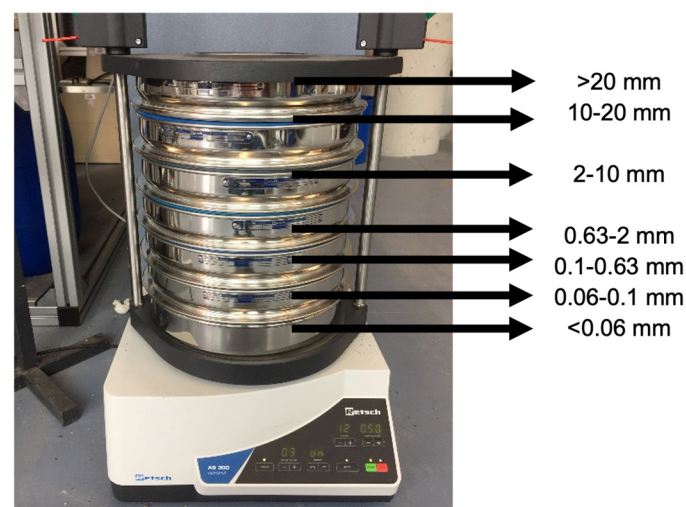


Figure 1. Vibratory sieve shaker and sieve sizes.

The contents obtained from each sieve were weighed, and a 0.06–2 mm fraction was used to obtain sand content data from the substrates. To determine and exclude organic content, the VS content of each fraction was determined, which was used to calculate the real sand content in the samples.

2.6.2. Assessment of the Impact of the Sand Content on the Biomethane Potential of the Biowaste

In this analysis, dried, ground substrate from substrate storage (which is currently fed into the biogas reactor) was used. The substrate–sand mixtures were prepared in the following way:

- (1) Blank: Only digestate,
- (2) No sand in the substrate: Dried substrate (100%) + digestate,
- (3) 10% (*w/w*) sand in the substrate: Dried substrate (90%) + sand (10%) + digestate,
- (4) 20% (*w/w*) sand in the substrate: Dried substrate (80%) + sand (20%) + digestate,
- (5) 40% (*w/w*) sand in the substrate: Dried substrate (60%) + sand (40%) + digestate.

Approximately 200 g of digestate was mixed with approximately 8.4 g of total mass (substrate–sand). The test was performed in an AMPTS II test system at 55 °C, following the same procedure mentioned above for other analyses (Figure 2).



Figure 2. Laboratory setup for the AMPTS II Test System.

2.7. Determining the Impact of the Leachate Addition Amount on the Biomethane Efficiency

As has been mentioned, the studied plant consists of a biogas plant and a composting plant. To improve the efficiency of the biogas, plant leachate from the composting plant is used, which can have high acidic content. The possible negative impact of leachate on the efficiency was evaluated in this section. Four scenarios were implemented based on scaling down the reactor and leachate volumes from real scale to the laboratory reactors. The reactors were prepared as follows:

- (1) Blank: Only digestate,
- (2) No leachate in the system: <60 mm biowaste + digestate,
- (3) 4.5 mL leachate: <60 mm biowaste + digestate + 4.5 mL leachate,
- (4) 2.3 mL leachate: <60 mm biowaste + digestate + 2.3 mL leachate.

Approximately 200 g digestate and 20 g substrate were mixed in the 500 mL reactors. The same procedure was implemented as in the previous analyses. A BMP test system with a eudiometer was used for this analysis as can be seen in Figure 3.



Figure 3. Laboratory setup with a eudiometer for the BMP Test.

For the experiments, the samples were taken at different points in the plant at different times. The first samples were taken in July 2021 in the two-stage dewatering unit of the biogas plant, and the second sampling took place in September 2021 in the digester.

3. Results and Discussion

This section is classified under five subsections based on the defined possible root causes (in Section 2) of inefficient biomethane generation in the biogas plant. The possible reasons are:

- (1) Loss of possible substrates due to the different biowaste streams,
- (2) Addition of leachate to the system,
- (3) High biowaste sand content,
- (4) Long biowaste storage time after arriving at the plant,
- (5) Short HRT.

3.1. Results of Evaluating the Impact of the Substrate Waiting Time

In general, biowaste is collected once a week from households and brought to the studied biogas plant. Varying amounts of waste collected in different seasons causes the accumulation and a long waiting time (up to 21 days) of biowaste. The aim of this experiment was to determine the impact of the substrate waiting time on the biomethane generation efficiency. From the first storage area, fresh substrate (which had arrived on the analysis day) and stored substrate (which had waited 14 days) were analyzed. In addition, to evaluate the current situation, old substrate from substrate storage (just before feeding it to the fermenter) was collected.

The TS contents of the analyzed substrates were as follows in Table 2:

Table 2. TS contents of analyzed substrates.

	TS (%)
Fresh substrate	38.55 ± 4.96%
Stored substrate	41.98 ± 0.45%
Old substrate	58.17 ± 4.91%

In addition, VS analyses were as follows in Table 3:

Table 3. VS analysis of the substrates.

	VS (%)
Fresh substrate	40.63 ± 1.02%
Stored substrate	52.11 ± 2.43%
Old substrate	58.18 ± 4.91%

As represented in Table 4, the highest specific biomethane production was obtained from fresh substrate:

Table 4. Specific Biomethane Production of the substrates.

	Specific Biomethane Production
Fresh substrate	324.5 ± 14.4 NmL (g VS) ^{−1}
Stored substrate	215.2 ± 20.6 NmL (g VS) ^{−1}
Old substrate	175.9 ± 12.2 NmL (g VS) ^{−1}

The results showed that almost half of the biogas capacity of the substrate was lost due to the waiting time in the arrival/storage area. Furthermore, the loss could also be caused by the inclusion of 60–120 mm and >120 mm particles in the fresh substrate as well as in the old substrate.

From biowaste's generation to its arrival at the facility, its water content starts to evaporate and its material starts to degrade [23]. The physicochemical characteristics of the biowaste change and the hydrolysis process starts, which leads to aerobic and anoxic conditions that are already in the produced biowaste within the storage time. A study performed by Degueurce et al., (2020) showed that 61–70% of the initial material remains at the end of the storage period and leads to a 44% decrease in the BMP potential [24]. This study's results show a similar trend that must be optimized for a more efficient process.

3.2. Results of the Impact of Input Streams on the BMP Potential

At the biogas plant being studied, the input stream is sorted based on the size of the material—<60 mm, 60–120 mm, and >120 mm. The fractions 60–120 mm and >120 mm are sent directly to the composting plant. This test's target is to evaluate the usage possibility of these two streams in the biogas plant and compare them with the current situation. The specific BMP results of these streams are as follows:

- (1) $770.6 \pm 93.3 \text{ NmL (g VS)}^{-1}$ for the stream >120 mm,
- (2) $441.8 \pm 41.3 \text{ NmL (g VS)}^{-1}$ for the stream 60–120 mm,
- (3) $242.2 \pm 44.4 \text{ NmL (g VS)}^{-1}$ for the stream <60 mm.

The results show that unused substrate streams at the biogas plant have greater BMP potential than the used stream, as represented in Table 4.

The TS and VS contents of those streams are:

- (1) $39.14 \pm 0.92\%$ TS and 56.24 ± 1.47 VS for <60 mm,
- (2) $37.93 \pm 1.21\%$ TS and 26.74 ± 0.44 VS for 60–120 mm,
- (3) $28.14 \pm 3.13\%$ TS and $22.53 \pm 0.65\%$ VS for >120 mm.

3.3. Results of Sand Analysis

Impurities (plastic bags, glass, stone, sand) in the biowaste can cause component failure and pipeline blockage [5,20–22]. This test aimed to measure the biowaste's sand content and determine how it impacts the BMP capacity.

3.3.1. Results of the Sand Fraction Determination

As mentioned in this paper's Section 2, the dried biomass was classified under seven different sizes, and three different sizes are used to determine the biowaste's sand content. All fractions detected in biowaste are summarized in Figure 4.

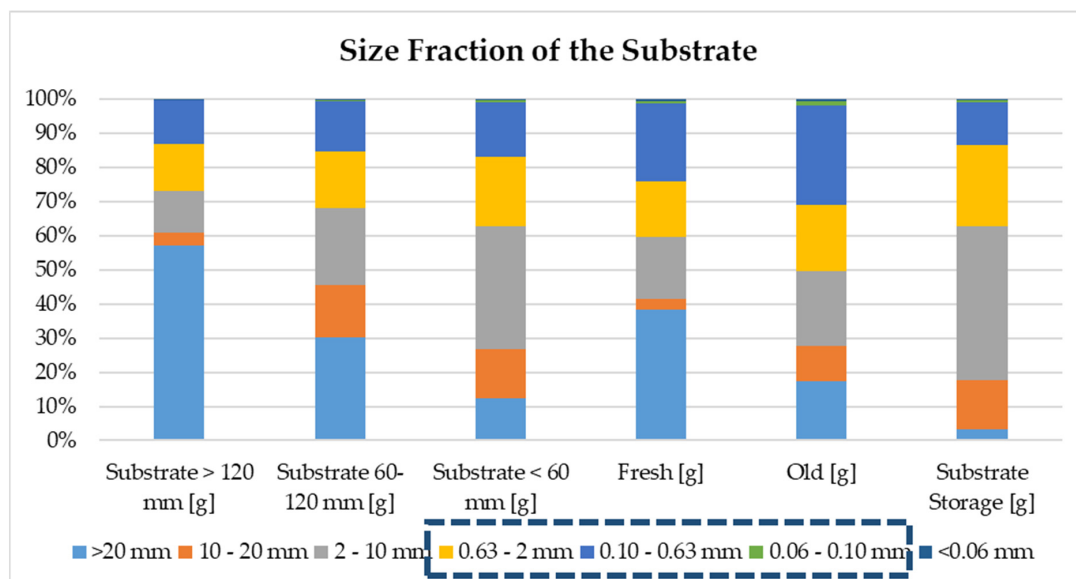


Figure 4. Size Fraction of the Substrate.

After the VS and TS analyses of each fraction, sand in TS and sand in VS were obtained as a mass percentage (see Table 5). The highest sand content was obtained from old substrate, followed by fresh substrate.

Table 5. Sand content in dry biowaste and fresh biowaste.

	Sand in TS (%)	Sand in FM (%)
Substrate Fresh	28.3	10.9
Substrate Old	34.9	20.5
Substrate Storage	20.7	8.7
Substrate <60 mm	24.1	9.6
Substrate 60–120 mm	17.6	6.8
Substrate >120 mm	12.3	3.5

3.3.2. Results of the Determination of the Biowaste Sand Content Impact on the BMP Efficiency

Since different substrate streams contain varying sand contents, the impact of the sand content on the biomethane production efficiency is an important parameter for a biogas plant. Four different scenarios were used in this test to analyze the necessity of pretreatment to remove sand from the biowaste. The chosen sand contents (% *w/w*) were:

- (1) No sand,
- (2) 10% sand,
- (3) 20% sand,
- (4) 40% sand.

As displayed in Figure 5, an increase in the sand content and a decrease in the organic content in the biowaste led to a decrease in the daily/cumulative biomethane generation.

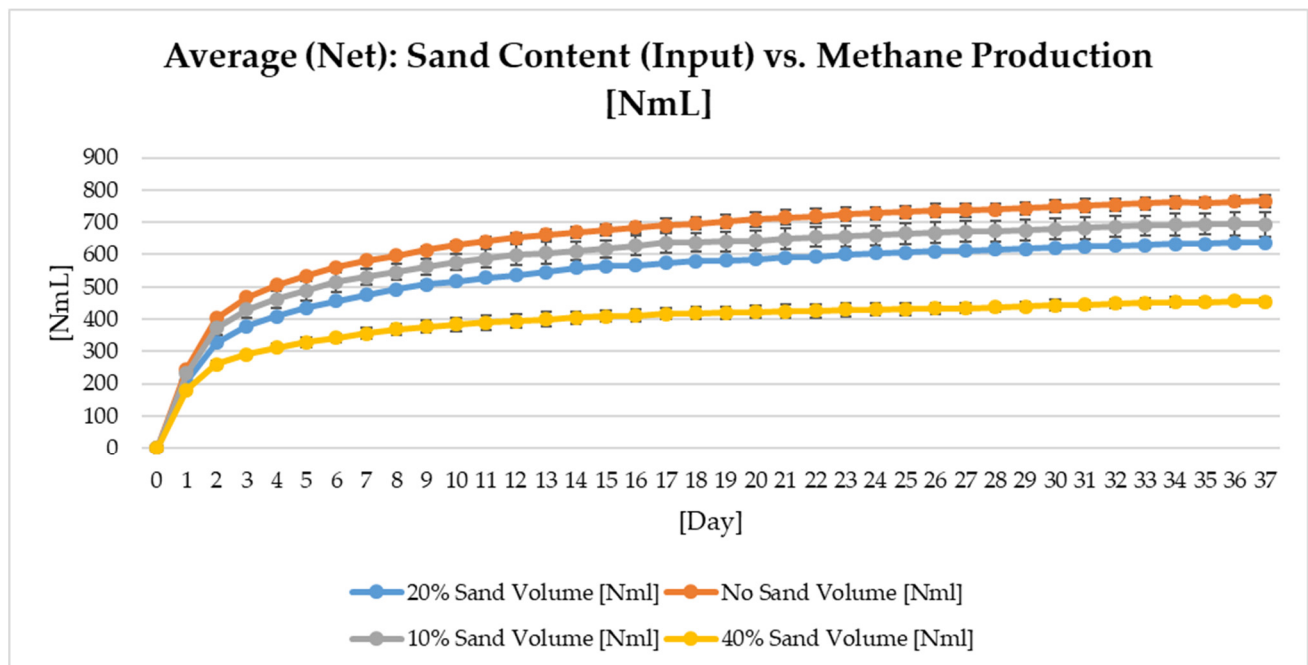


Figure 5. Methane Production under different sand contents.

Since the same biomass was used in each reactor, specific biomethane generation under different sand concentrations did not vary much, which shows that the sand content's impact on the contact between microorganisms and the substrate was negligible in small-scale reactors. However, this kind of problem may occur in a large-scale plant as well as the accumulation of inorganics in the reactor within the operation time [16].

3.4. Results of the Impact of Leachate Recirculation on the Biogas Reactor

Leachate in a composting plant is generated from the biowaste's water content. To improve the microbial community in the anaerobic digestion process, leachate is added to the substrate before feeding it into the digester. Three different leachate concentrations were determined by scaling down the reactor size and the substrate feeding amount. The amounts of leachate were determined as:

- (1) 0 mL,
- (2) 2.3 mL,
- (3) 4.5 mL.

Figure 6 displays the results of the BMP test with different leachate concentrations. The specific BMP under varying leachate concentrations had negligible differences:

- (1) 205.6 ± 21.3 NmL g VS-1 from the reactor with no leachate,
- (2) 210.5 ± 18.7 NmL g VS-1 from the reactor with 2.3 mL leachate,
- (3) 213.3 ± 31.9 NmL g VS-1 from the reactor with 4.5 mL leachate.

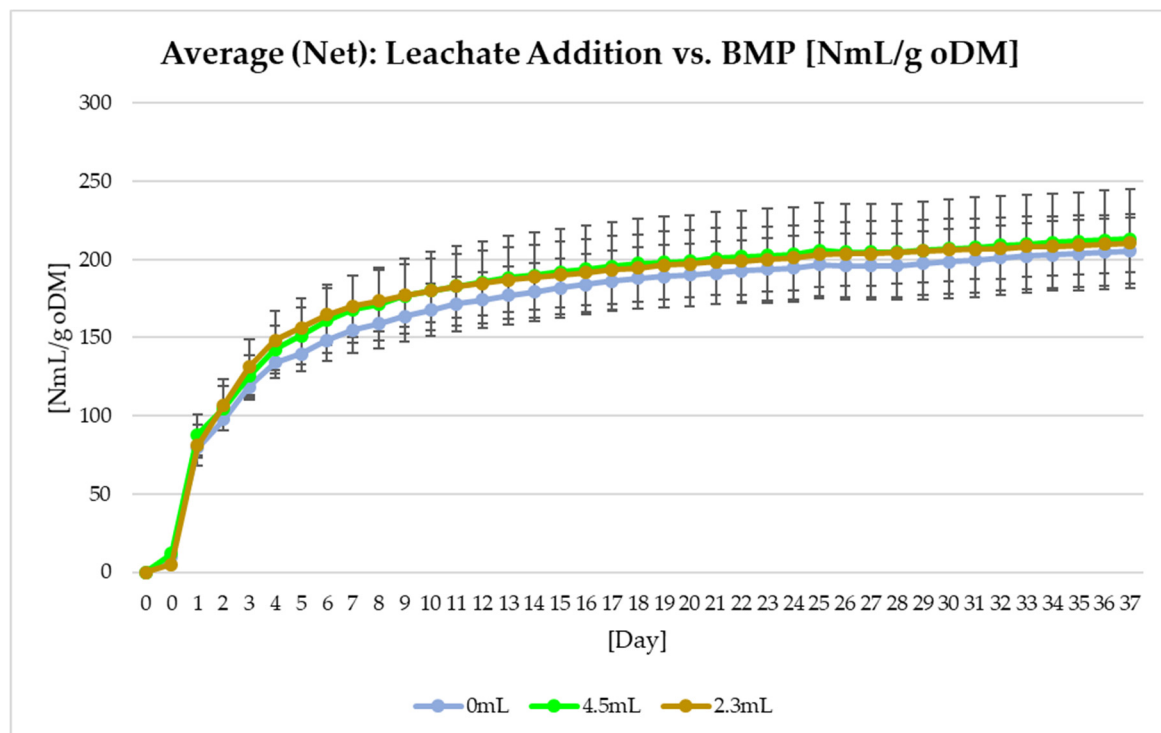


Figure 6. BMP under different leachate amounts.

The addition of leachate led to a slight increase in the specific biomethane generation from biowaste.

Composting leachate results in a high amount of dissolved salts, organic matter, ammonia, pathogenic microorganisms, and heavy metals. Immature composted leachate has an acidic pH, and mature leachate has an alkaline pH [25]. The pH of the leachate sample in the biogas plant showed that the leachate was mature leachate with a pH value of 8.54 [25]. Therefore, an increased amount of leachate did not cause an acidic environment or a negative impact on the system.

3.5. Results of Current HRT Evaluation in the Studied Biogas Plant

Another potential reason of inefficient biogas production was the HRT of the biogas plant, which could be too short for the processed substrate. The samples from the digester were collected in two different months (July and September). Since aerobic/anaerobic digestion in the storage of biomass happens especially in summer, different results from

those two samples were obtained as presented in Table 6. Similar results to the biogas generation results of an industrial-scale digester were obtained from those samples with lower production in summer months. The biogas generation from residual biomass was not high and did not increase the capacity of the digester.

Table 6. Methane Production by Inoculum.

Experiment	1	2	4	5
NmL	436.30 ± 12.72	490.40 ± 56.45	837.13 ± 23.46	958.61 ± 39.23
NmL/g oDM	22.63 ± 0.94	22.76 ± 2.79	40.06 ± 1.12	45.77 ± 1.79
NmL/g FM	2.54 ± 0.11	2.81 ± 0.35	4.17 ± 0.12	4.77 ± 0.19

As explained in Section 2 of this paper, pH measurements were performed before and after BMP analyses, and the results are displayed in Table 7. The pH value in the reactors fluctuated between 7.93 and 8.24, and pH measurements before and after the test showed that the pH value within the test period stayed almost stable. The reason for high pH in the second set of experiments at the beginning was the delayed start of this test compared to others. The two-day incubation of the inoculum at 55 °C increased the pH value.

Table 7. Results of pH measurements before and after BMP tests.

Analyze	Content	pH—Before	pH—After
Substrate waiting time	Fresh (freshly arrived)	8.05 ± 0.10	8.07 ± 0.09
	Long (waited in the arrival area approximately 14 days)	8.13 ± 0.05	8.10 ± 0.13
	Substrate storage (just before feeding into reactor)	7.96 ± 0.08	8.18 ± 0.13
Substrate stream	Substrate size <60 mm	8.24 ± 0.08	7.93 ± 0.13
	Substrate size 60–120 mm	8.22 ± 0.03	7.98 ± 0.10
	Substrate size >120 mm	8.22 ± 0.11	8.00 ± 0.02
Sand content of the substrate	Substrate does not contain sand	7.93 ± 0.11	8.10 ± 0.06
	Substrate contains 10% sand	7.98 ± 0.02	8.13 ± 0.10
	Substrate contains 20% sand	8.10 ± 0.06	7.96 ± 0.04
	Substrate contains 40% sand	8.08 ± 0.08	8.08 ± 0.06
Addition amount of leachate to the system	No leachate addition	8.05 ± 0.04	8.07 ± 0.14
	2.3 mL leachate addition to the lab-scale reactors	8.07 ± 0.22	8.08 ± 0.06
	4.5 mL leachate addition to the lab-scale reactors	8.02 ± 0.06	8.09 ± 0.05

In order to interpret all experiments conducted in this study in light of the LSS methodology, the *p*-value for each experiment should be calculated using hypothesis testing. Due to the nature of the factors compared in the experiments, one-factor ANOVA and 1-sample Z-test were used to calculate the *p*-value for each possible cause. Since three or more factors were compared in the experiments, except for the effect of HRT, one-factorial ANOVA was used to calculate the *p*-value for examining the effects of possible causes such as the waiting time of the substrates, addition of leachate to the system, sand content, and different sizes of substrates. A 1-sample t-test was used for the effect of HRT since only one factor was involved in this analysis. Each possible cause that has a *p*-value less than 0.001 can be considered the cause of the problem. In our study, the particle size of the substrate, the freshness of the substrate, and the sand content were the root causes, which underlines the importance of pretreatment methods in a biogas plant.

4. Conclusions

This work studied the DMAIC methodology's analysis phase in an effort to improve biogas production in a biogas plant in a laboratory environment. Our results demonstrate the importance of pretreatment methods in terms of impurities and particle size, as well as the substrate's waiting time for the optimization of biogas production. With the collected

results of the experiments, it is possible to perform hypothesis testing to determine the p -value for each scenario. However, as mentioned earlier, the objective of this study is to provide an aspect for the analysis phase of the Lean Six Sigma methodology. By using the scaled-down approach, it is possible to sample the entire system in a laboratory setting. As a whole, this work provides a new perspective on process optimization in anaerobic digestion. Statistical approaches in biogas technology can be applied using laboratory experiments without disturbing day-to-day operations, as long as a logical scale-down is possible.

For future research, a wider range of operating procedures could be used for different problems to determine a better biogas production environment. In addition, for accuracy in further studies and applications, experiments could be conducted in continuously stirred-tank reactors (CSTR).

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