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MITIGATING TECHNICAL AND OPERATIONAL FAILURES IN THE DESIGN AND MAINTENANCE OF BIOGAS PLANTS

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Abstract: Biogas plants offer significant opportunities for sustainable rural development and diversification of energy supply, but recurrent technical and operational failures threaten their performance and long-term viability. This article systematically analyses the most common problems in construction, maintenance and operation, including structural defects, plant malfunctions and inadequate safety protocols. The focus of this study is to identify root causes - such as design flaws, material incompatibility and improper coordination of workflows - and to suggest advanced engineering and management solutions to prevent costly failures. By incorporating insights from actual case studies, the article offers practical recommendations for improving reliability, safety and profitability in modern biogas plants.
Key words: biogas plants, technical failures, design, construction, maintenance, operational risks, reliability

INTRODUCTION

Given the global rise in energy demand and worldwide efforts to reduce pollution, new, cleaner energy sources are becoming increasingly important. The World Bank predicts that high-income countries will see a 19% increase in daily per capita waste, while low- and middle-income countries will experience more than double that rise [1]. A major problem is that most of the world's agricultural waste is disposed of in unregulated landfills or burned openly. The use of organic waste for energy aligns with the principles of a circular economy and helps to reduce greenhouse gas emissions. Therefore, a growing number of studies and technological solutions are focused on sustainable energy sources, including energy derived from various biofuels such as ethanol and biogas [2]. In countries with substantial agricultural and livestock production, there is great potential for using environmentally friendly biogas technology as a renewable energy source [3]. In 2022, the total biogas production in the entire EU was 16.8 billion m3, and biomethane production was 4.2 billion m^3. These amounts are considered insufficient, and it is believed that the EU needs to increase production from these types of facilities. European countries commonly use biogas as a fuel in combined heat and power (CHP) units to generate both thermal and electrical energy, which is considered a highly efficient use of gas. Part of the produced electricity is used for the plant's own consumption, while the majority is supplied to the electrical grid [4]. The input material for bioenergy or biogas plants can be organic waste from agricultural and livestock production, as well as waste from the food processing industry, catering, and municipal sources [5]. A decade ago, Croatia promoted the production of electricity from biogas power plants and, through subsidies, invested over 331.81 million euros at the time, with owners of biogas plants investing even more. According to 2022 data, Croatia has 42 biogas plants and no biomethane plants. In that year, Croatia produced 0.11 billion m^3 of biogas, while the share of biogas in the natural gas supply in 2021 reached 4.1% [6]. Today, most of Croatia's biogas plants are in Slavonia, specifically in the Osijek-Baranja and Vukovar-Srijem counties, which have the largest number of farms [7]. Previous practices in Croatia point to several issues across all phases of bioenergy plant development, as well as with related legal regulations and market operations, all of which ultimately raise questions about their profitability and continued operation.
This paper identifies and analyzes specific shortcomings and errors in planning and design, construction, and maintenance of these plants. By implementing appropriate improvements, it

would be possible to achieve a significant reduction in the operating costs of these bioenergy plants. Recent research has focused on practical problems and technological solutions related to the planning, design, implementation, and operation of bioenergy plants. According to Saidmamatov et al. [8] biogas production can have a fivefold benefit by developing a local energy source, mitigating negative environmental impacts, reducing methane emissions, producing organic fertilizer as a byproduct, and providing additional income for farmers [8]. However, producing energy from biogas requires appropriate infrastructure, well-built and maintained facilities, as well as a transformation of the production practices in the sector that supplies the necessary organic materials [9]. The primary objective of a study by Singh et al. [10] was to highlight the practical challenges concerning the planning, design, monitoring and control systems, cost-benefit analysis, resource management, and optimization aspects for decentralized biogas plants, for which they conducted a comprehensive review of relevant literature. Activities both before and after the planning, design, and infrastructure development of decentralized biogas plants play a vital role in their sustainable and long-term operation [11]. Challenges in the pre-planning phase include conducting thorough feasibility studies and site assessments to identify an optimal location, as well as finding suitable raw material sources to ensure a consistent supply of organic waste [12]. Challenges related to post-planning activities encompass regular monitoring and maintenance, gas storage and utilization, securing a skilled workforce, and implementing safety measures such as managing odors and sludge, preventing gas leaks, and avoiding explosions [13]. Simultaneously, careful consideration of design and infrastructure development is also crucial for the smooth operation of these plants [14]. The main difficulties in this phase involve selecting the appropriate digester technology based on the availability of raw materials [15]. The use of poor-quality materials can compromise the structural integrity and longevity of a plant, leading to potential leaks, material degradation, and reduced efficiency [15,16]. Different technologies come with varying financial implications, and assessing long-term economic viability is essential for making informed decisions. Based on scientific and practical aspects, Gadirli et al. [2] conducted a study that focused on the design, construction, functioning, and operation of biogas plants in Poland. In their work on bioenergy production in Pakistan, Afridi and Qammar [3] identified problems in fundamental infrastructure, such as leaks from gas pressure, inadequate digestate removal, and a lack of a mechanism to prevent deposit formation and steel corrosion, and they proposed solutions.

TYPICAL BIOGAS PLANT SYSTEM

A biogas plant is a complex facility whose design depends on the type and quantity of raw materials used for biogas production (Fig. 1.).

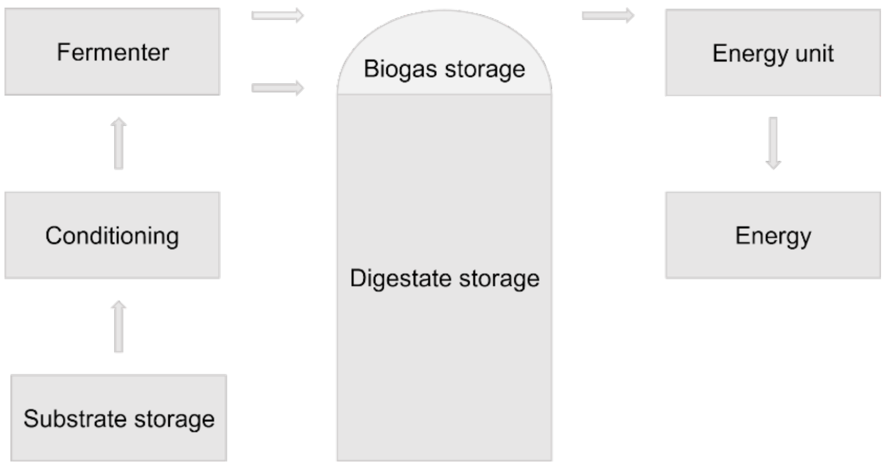

Fig. 1. *Biogas plant components diagram*

The main components of a typical biogas plant include: the feedstock reception and storage area, where raw materials like silage are received and stored. The digester is the most crucial part of the plant, where raw materials are heated and mixed with water and microorganisms to produce and collect biogas. Other key parts are the biogas storage tank and the digestate storage unit, which holds the high-value organic fertilizer byproduct. The plant's operational infrastructure includes pump stations, as well as various pipelines, valves, and fittings to manage the flow of materials. The produced biogas is then converted into electrical and thermal energy in cogeneration units. The facility also contains a control unit for managing the process, a weighbridge, conveyors for material transport, and internal roads for logistics. Most structures are partially buried to accommodate pipelines that transport liquid feedstocks, digestate, and gas. These plants are typically built on large plots of land, often near rural areas, to connect to electricity and water supplies. Construction of a biogas plant is a demanding process, requiring the expertise of civil, mechanical, and electrical engineers. Challenges arise from working outdoors and from the increased construction demands for handling corrosive content. Heightened safety measures are essential to prevent potential explosions caused by the large quantities of methane produced during the process.

PLANNING AND DESIGN OF BIOGAS PLANT

This chapter outlines the key steps in building a biogas plant. These plants typically consist of a digester, and a secondary digester with identical dimensions. The process begins with planning the plant's layout and designing the digesters, which includes a methodology for determining their dimensions and those of the residue storage tanks. After site investigations, including soil analysis and groundwater levels, the facility layout for a commercial biogas plant can be planned. Following the planning phase, the project is undertaken, involving excavation, preparing the digester's base plate, and installing heating tubes, insulation, and other necessary technology [17]. The operation of the plant includes the use of various mechanical systems, such as a solids feeder, gas processing unit, and mixing technology. Finally, the system control is established, which allows for both remote and on-site monitoring of all individual facility components via a computer system. After site investigations, including soil analysis and groundwater levels, the facility layout for a commercial biogas plant can be planned. These plants typically consist of a digester, and a secondary digester with identical dimensions.

Attached to the digesters is a residue storage tank. The solids feeder is located next to the digester, and the entire tank area is surrounded by a green belt, except for one side where the horizontal silos are situated. Conventional digesters, also known as rural digesters, are used to process liquid raw materials with a high solids content and typically have a fermentation chamber volume of less than 100 m^3. In biogas plants, cylindrical, cast-in-place concrete or steel tanks are often used to store liquid manure. These tanks must be watertight to prevent groundwater pollution and rebar corrosion and are designed to withstand both the load of the soil surrounding the buried section and the weight of the stored liquid. The dimensions of these large, partially underground tanks typically range from 18 to 33 m in diameter, with heights from 2.4 to 4.9 m, and a uniform wall thickness of 150 to 200 mm [18]. The depth of digging depends on the specifications of the soil. For commercial biogas plants with large digesters reaching up to 25 meters in diameter, the concrete structure must be reinforced. To achieve this, standard 12-meter iron rods are cut and used to construct two iron grids, which are erected from the digester's base plate. Formwork, made from either wood panels or pre-constructed metal sheets, is then used to enclose the grids and create a container for the fluid concrete. Once the digester wall is built, approximately one-third of the internal surface is covered with a protective layer to prevent corrosion.

Biogas plants commonly feature two primary types of digesters, each offering distinct advantages depending on the project's needs. Metal digesters, often constructed from prefabricated glass-lined steel, are valued for their quick installation and consistent manufacturing quality. In contrast, concrete digesters (Fig. 2.) are built on-site and are a robust, durable solution typically chosen for large-scale projects, with designs that can be partially or fully buried underground for stability and thermal insulation. Glass-lined steel provides superior corrosion resistance to most acids and chemicals, allowing digesters to operate for many years in extremely aggressive environments. However, this material is not without its challenges. At higher temperatures, glass becomes less effective against alkalis, and it is also very susceptible to impact damage during installation or operation. Such damage can create pinholes, which allow corrosive chemicals to attack the underlying steel. A major risk is that these defects can quickly lead to through-wall failures, resulting in the escape of liquid digestate or, more critically, methane gas. Methane can form an explosive mixture with air, which can be ignited by a spark from maintenance or static electricity. Because welding is too risky and can damage the glass lining, costly repairs must be performed using alternative solutions that cure at ambient temperatures, such as epoxy composites or prefabricated non-metallic patches.

Fig. 2. *Circular concrete digester*

In concrete anaerobic digesters, complications can arise from a cold start, before necessary bacteria are established, or when the digester is taken out of service, introducing oxygen and upsetting the pH. The presence of undigested volatile acids can also lower the pH and kick-start corrosion. When these issues occur, they primarily impact the biogas phase and the surface of the effluent substrate. Corrosion is caused by moisture reacting with contaminants like hydrogen sulfide (H_2S) to generate highly corrosive sulfuric acid. This acid attacks the vapor space at the top of the tank, the walls, the underside of the roof, and the internal pipework. Given that aging digesters require robust corrosion management strategies, non-metallic solutions like high-performance coatings have proven to be effective in extending an asset's lifetime and reducing maintenance.
The construction of a gas holder begins with building an umbrella-shaped wood or steel structure, over which a mesh network is laid. An air-supported double-membrane cover, which includes the gas holder, is then mounted over this structure. The inner flexible membrane of the gas holder is designed to move up and down in response to changes in gas pressure.
The technology installation phase involves setting up the essential internal components first, such as the filling indicator, tubes, measuring devices, and the electricity and fiber cable networks. Following this, the gas collector is installed along with the excess and low-pressure safeguards and the air support fan. This is the process of insulating the digester, which is a critical construction step that should be performed carefully and accurately. The digester is lined with either mortar containing 1% silica, followed by a coat of petroleum albumen, or with foam sheets. In other designs, the walls are heat-insulated with non-corroding and weather-proof aluminum trapezoidal panels. In contrast, rural digesters are typically coated with layers of dry dirt and asbestos.
However, once these assets are built, a new set of challenges arises. Despite the best construction practices, the operational environment of a biogas plant is extremely aggressive. When designing biogas plants, safety issues are just as vital as technological aspects. The system's elements must be arranged to prevent the domino effect, where damage to one element leads to a fire that affects others. For instance, low-pressure tanks require a minimal distance of 9 meters from other elements, while high-pressure tanks need at least 50 meters

due to thermal radiation risks. Similarly, zones where flammable gas concentrations exceed safe limits must be free of ignition sources.

CLASSIFYING COMMON SOURCES OF HAZARDS AND INCIDENTS IN BIOGAS PLANTS

Common sources of hazards in biogas plants

This chapter provides an overview of the main sources of hazards in biogas plants. The history of failures and accidents in biogas plants demonstrates that the total elimination of hazards in this sector is not feasible. However, it is possible to influence some of the hazards during the construction process itself, with examples of poorly executed works presented in Table 1.

Table 1. *Common hazards in biogas plants: failures due to construction*

Hazard	Failures due to construction	Consequences
Fire and explosion	Instability of the gas storage components, incorrect assembly of gas storage elements, unevenness on the concrete crown of the storage tank	 
Biohazard	Improper and insufficiently executed protection and waterproofing of surfaces through which dangerous substances penetrate into the soil—floors and walls of the storage tank, fermenter (digester), lagoon	 
Electric	Improper execution and protection of electrical installations, penetration of moisture and water into areas where the installations are located	 

Mechanical	Improperly prepared foundation and installation for positioning mechanical equipment, as well as pipes that transport raw materials, gas, and digestate	 

Although biogas production has significant environmental benefits, these facilities involve risks related to fires, explosions, and biological and mechanical hazards. These hazards will now be described, covering those that are possible during the exploitation of a biogas plant. For a better overview, Table 2 with the listed hazards, their causes, and mitigation techniques is provided [19].

Table 2. *Sources of hazards in biogas plants, their contributing factors, and mitigation techniques*

Hazard	Contributing factors	Mitigation technique
Fire and explosion	The risk of a fire or explosion, exist when the concentration of methane in the air is within the range of 5% to 15%	Monitoring and control Ignition source control System design and maintenance
Biohazard	Presence of microorganisms, such as bacteria, viruses, fungi, and parasites, in the organic waste feedstock	Monitoring and control Hygiene standards Disinfection
Electric	Electrical equipment that is not properly installed or maintained	Regulations and standards Design and installation Maintenance
Mechanical	Frequent use of heavy gear and equipment with moving parts	Proper machine guarding Regular maintenance Adequate training

Biogas is a flammable gas that presents a fire and explosion risk if it encounters a spark or flame. Mixtures of air and methane pose a particular danger and can ignite at a methane concentration between 5% and 15%. Under ideal conditions, when the mixture is near its stoichiometric ratio, a powerful explosion can occur, making it crucial to monitor and manage gas concentration within the plant. Biohazards stem from the nature of the raw materials used, including manure, food waste, and sewage sludge. These materials can contain various microorganisms like bacteria, viruses, and fungi that can threaten workers' health, potentially causing gastrointestinal illnesses or skin and respiratory infections. To prevent these risks, it is essential to use appropriate personal protective equipment, adhere strictly to hygiene standards, and perform regular disinfection of equipment and work areas. Mechanical hazards at the plants are significant due to the use of heavy equipment and moving parts. Workers are at risk of crushing, entanglement, and amputation injuries. It is vital to carefully assess and mitigate these risks through proper machine guarding, regular maintenance and inspections, and providing adequate training for staff. Electrical hazards are present due to the extensive use of electrical equipment. Improper installation or maintenance can lead to electric shock or fire. Because of this, strict standards and regulations have been developed by international organizations and national governments. These regulations ensure the safe design, installation, operation, and maintenance of electrical systems, thereby protecting workers and the environment.

Common causes of incidents

Incidents in biogas plants, which can range in severity, are typically caused by a variety of factors. These can include human errors in operations and maintenance, equipment and component failures, and natural or technological disasters. The severity of these incidents, which can manifest as accidents, is determined by factors such as the type and location of the event, as well as the effectiveness of the existing safety measures [19]. Accidents in the biogas sector are typically caused by equipment and component failures, design errors, and improper operation or maintenance. Across the broader bioenergy sector, a majority of accidents are a result of fires (53%) and explosions (40%), with a smaller percentage (7%) related to toxic releases [20].

As previously mentioned, accidents can be the result of a combination of various factors, including maintenance error, equipment failure, operational error, component failure, and natural disasters (Table 3).

Table 3. *Common types of accidents and their descriptions*

Accident	Description
Maintenance error	Improperly inspecting or replacing equipment. Regular maintenance is essential for safe and efficient operation
Equipment failure	Leaks or malfunctions (electric and mechanical hazards), can occur, resulting in occurrences and injuries
Operational error	Misinterpreting data or failing to follow proper protocols can lead to significant causes of biogas plant occurrences
Component failure	Component failure is a common cause. Parts can fail due to normal wear and tear, corrosion, and fatigue
Natural occurrences	Natural occurrences such as floods, earthquakes can cause equipment damage or structural failures

Since biogas plants are a relatively new type of industrial facility, safety regulations for them have not been fully developed [21]. Understanding the range of hazards and causes of accidents in biogas plants is essential for ensuring safety. It is also important to recognize that the unique variables of biogas facilities can make their occurrences distinct from those in other industries. Therefore, further research is needed to overcome the challenges of data underreporting and to establish clearer causal relationships to continue to enhance safety protocols.

CONCLUSION

The construction and operation of a biogas plant is a highly complex process, requiring diverse expertise and facing an extremely aggressive operating environment that threatens material integrity. While biogas production offers significant environmental benefits, the inherent nature of the process means the complete elimination of hazards is not feasible. Risks such as fire, explosion, biohazards, and mechanical/electrical failures are constantly present, often stemming from design flaws, equipment failure, or human error.
Although biogas plants are conceived as a smart and ecological way to manage waste and generate environmental profit, they can sometimes turn into the site of ecological and material disasters. The most crucial element throughout the entire process of plant construction and operation is the human factor. Project designers and contractors bear immense responsibility, as irregularities in execution can significantly contribute to poor operating outcomes.
To ensure both safety and long-term viability, a proactive strategy is essential. This includes careful analysis of system element placement during design to prevent cascade failures, employing effective mitigation techniques (like gas content monitoring and regular

maintenance), and upgrading existing technological options. Furthermore, the successful implementation of biogas projects requires an integrated approach to managing the entire supply chain and logistics, alongside crucial investment in training programs for technicians and operators to ensure the availability of a skilled workforce for long-term success.

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