

A
Research Project
On
Bioprocess Safety:
Process Safety related Hazards and Risks
Associated with
Emerging Technology

By:

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Summary

Bioprocess is a specific process that uses bacteria, and enzymes to form useful products. There are major three emerging industries which lead to large-scale manufacturing through bioprocess are biopharmaceutical, renewable resource, and environmental. Currently, these industries are growing but the risks and hazards related to these industries are not much familiar. So to avoid the risk of an incident the knowledge of the safety related to the bioprocess is necessary. In this report, the risks and hazards of biogas production are discussed. Day by day Biogas usage is increasing as part of an alternative source of fuel. In the last two decades, the increase in the biogas production facility is less compared to the rise in the number of incidents. In this research, the risks and possible hazards related to biogas production through an anaerobic process are described. Literature regarding accident analysis, safety barriers, the procedure for safe operation common safety practices, and possible hazards are analyzed. Based on an examination of accident frequency and consequences, a risk assessment has been conducted. In this report, different biogas incidents are examined which happened from 2004 to 2016. For this sector, a non-negligible risk profile is generated, which exposes a developing risk problem. Based on the various reasons, the previously happened incidents are divided into different categories. From the investigation through incidents, explosions and leakage of biogas cause the major problems in the biogas plant along with the toxic biomass spread. These hazards mainly occur due to operational and maintenance problems. The operational error can be reduced by implementing the safer practices that are stated in the report, while maintenance and other errors can be eliminated by establishing a safety culture in the facility. To avoid the accident before it happens, risks need to be identified thoroughly by an improved risk assessment method because an improper investigation always results in data deficiency that makes it difficult to interpret the results. For health-related hazards, it is recommended to follow OSHA regulations while working. To eliminate process-related hazards, it is needed to follow safety guidelines and precautionary steps.

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1. Introduction

With the help of live cells and their components, people have been able to bake bread, manufacture cheese, and ferment alcoholic drinks from the dawn of time (bacteria, enzymes). The production of polymeric materials and biofuels from sustainable biomass feedstock is one of the expanding emerging technologies that rely on bioprocessing. Both biological and chemical risks might exist in a bioprocessing facility. However, there aren't any comprehensive methods for risk assessment in this field. Few researchers have attempted to alter traditional risk assessment techniques but still amendments require for appropriate risk assessment method. The focus of process safety management has typically been on large facilities producing chemicals, polymers, petroleum, and natural gas; however, other facilities in the process industries have also heavily utilized and profited from the basic principles. But in the case of bioprocessing industries, there is no particular bioprocess safety management. General belief that the bioprocess is safer than the conventional chemical manufacturing facilities but the incidents happened in past two decades makes us to rethink about the safety.

The rise in activity, particularly in bioprocesses, has caused process safety management to unchanged. This delay in updating the laws and regulations used to govern bioprocesses has prompted incident investigations to find the management system's shortcomings. The performance of bioprocesses may be impacted by unmanaged risk factors, leaving the business vulnerable to losses and a reduction in process safety performance. The goal of this research is to pinpoint the major flaws and suggest a solution for the many risks that have been connected to production of biogas through anaerobic digestion (bioprocess). The increase in the demand of sustainable energy accelerates biogas production. The increasing biogas facilities also bring the new hazards related to the production and process. So it is recommended to follow safety precautions and guideline for this new emerging technology.

2. Objective

The biomaterials that are used to make fuels are essentially byproducts of plants or animals that, when subjected to anaerobic decomposition, provide energy by anaerobic process. It has been suggested that using biofuel to produce energy is a better path than using fossil fuels. The adverse effects that fossil fuels have on the climate are another drawback. As a result, it has been believed that gathering energy sustainably is the solution to the sustainability issue plaguing the energy industry. Alternative energy source biomass that includes biogas manufacturing is one of the emerging industries in the past twenty years.

Biogas is formed when bacteria consume biomass from domestic waste, wastewater treatment sludge, and agricultural waste. It must be required to assess the various types of biogas in order to adequately assess the risks connected with them. Landfill gas is a type of biogas that naturally develops in-home waste landfills, whereas digester gas is created through an induction process in a bioreactor or a digester. The garbage and the procedure utilized both affect the biogas's composition. In determining the content of the biogas, time is another important aspect. Methane and carbon dioxide are the main substances in biogas. Hydrogen sulfide, hydrogen, and organosulfur are further components that are present in trace amounts and are depicted in Table 1. Numerous researchers have assessed the potential risks related to the production of biogas in which potential explosiveness, toxicity, hypoxia, loss of containment through rupture and leakage in equipments are the main results. These risks are mostly responsible for damages because of process pressurization, equipment failure, inadequate operating training, and a lack of a safety culture. Therefore, it is necessary to identify the risks related to the biogas process in order to prevent future incidents.

Table 1: The Composition of biogas

Compound	Household waste (%)	WWT Sludge (%)	Agricultural waste (%)
Methane	50-75	60-75	60-75
Carbon dioxide	25-50	19-33	19-33
Nitrogen	0-10	0-1	0-1
Hydrogen	0-1	0-0.5	0-0.5
Hydrogen Sulfide	0-3	0-2	3-10
Oxygen	0-1	0-0.5	0-0.5
Ammonia	0-1	0-1	0.5-1
Water	0-10	0-6	0-6

3. Literature Review

Analysis of accidents in biogas production and upgrading, by Valeria Casson Moreno, Salvatore Papasidero, Giordano Emrys Scarponi, Daniele Guglielmi, Valerio Cozzani [1]

The literature gives the information about the incidents related to biogas facilities are increased as the biogas production increased over the world. To find connections between accident causes and scenarios, Multi Correspondence Analysis is used in the research to examine the causes of accidents, scenarios, and repercussions of biogas occurrences. A risk assessment is conducted, and the outcome shows a non-negligible risk profile to other threats. Based on the errors and failures made during the operation, these situations' causes are grouped. To create a safe atmosphere, the errors and causes of failure must be removed. Adopting design standards and safety protocols used in other industrial domains might have averted the majority of accidents. Therefore, one primary underlying reason for the large number of incidents reported in biogas production and upgrading is the lack of specified worldwide technical standards and norms. The results of the accident study serve as a forewarning about the serious accident risk in the biogas business and have sparked concern about the need to enhance the safety culture and risk awareness in this industry, as well as by creating and enacting adequate and precise safety regulations. The creation and implementation of particular safety standards for the biogas industry would be beneficial since the discovery and use of inherently safer technology is yet largely unexplored. Therefore, it would be advantageous to define and implement particular safety standards for the biogas industry to prevent design and operational mistakes.

Development of equipment and procedures for the safe operation of aerobic bacterial bioprocesses in the presence of bulk amounts of flammable organic solvents, by A. Schmid, A. Kollmer, B. Sonnleitner, B. Witholt [2]

The research emphasizes the necessity of tools and protocols for two-phase aerobic bacterial bioprocesses that employ flammable solvents. When using flammable organic solvents as substrates in an aerobic environment, the reactor's explosive atmosphere must be taken into account. A stirred tank bioreactor's liquid phase is sparged with air during aerobic bioprocesses. As a result, a mixture of vapors, liquids, gaseous oxygen, nitrogen, and carbon dioxide builds up in the reactor head area. The amount of organic vapor present in two-liquid phase processes can be large when volatile organic solvents, medium carbon-chain alkanes are present as a second liquid phase. A potentially explosive environment can form in the reactor's gaseous head region if the proper safety measures are not implemented. In anaerobic digester the ratio of carbon to nitrogen need to be maintained otherwise it increases the ammonia content which ultimately increase the asphyxiant gas content. These conditions lead to the over

pressurization, that increases the need for safety. As a result, creating and running such systems calls for extreme caution and should never be performed without supervision.

Identification of critical safety barriers in biogas facilities, by Valeria Casson Moreno, Daniele Guglielmi, Valerio Cozzani [3]

Increasing opportunities of manufacturing sustainable fuel from organic raw materials has led a fast growth in biogas sector. As quick growth in of production facility also increase the number of accidents. Biogas produced by the complex biological reaction with several hazards. The major hazard related to the manufacturing is majorly because of CH₄ and CO₂. These gaseous products may cause catastrophic rupture of digester which brings the problems: missiles ejection and blast wave if process is not taken care properly. Hydrogen sulphide is also caused corrosiveness and high toxicity. According to the researchers, medium- to small-scale biogas plants are often run by farmers with limited technical expertise. Therefore, it is obvious that the biogas industry has to create particular safety requirements, as well as enhance its safety culture and risk awareness. In this paper, a novel hazard intensification approach called DyPASI (Dynamic Procedure for Atypical Scenarios Identification) is combined with a traditional bow-tie methodology used in the investigation of major accident hazards. When dealing with fast-developing technologies like those employed in the biogas industry, it is essential to incorporate expertise derived from pre-warnings and new risk conceptions into the hazard identification methodologies. The integrated method used in this literature is essential for helping out to find the possible ways which may lead to incident.

Potential hazards posed by biogas plants, by Katarzyna Stolecka and Andrzej Rusin [4]

In the literature Katarzyna Stolecka and Andrzej Rusin studied how to increase the synthesis of biogas by implementing the anaerobic digestion method and what are the hazards associated with process. They have proposed that during the large scale of production, major accident happen either due to a failure of some biogas equipment or improper maintenance and operation personnel. The hazardous component carbon dioxide, ammonia, hydrogen sulfide and other flammable and toxic gases like carbon monoxide lead to significant hazard during uncontrolled release of biogas. The common risks in manufacturing of biogas are fire and explosions. When these gases are released, there may be risks associated to the presence of infections and harmful chemicals. Other incidents in the production of biogas are due to equipment and component failures, design flaws, improper operation, or maintenance. The Event Tree Analysis facilitates the quantitative evaluation of biogas plant risk. The conducted

research suggests that analysis of the biogas plant safety need to be implemented during design stage as well as during plant operation.

Common Safety Practices for on-farm anaerobic digestion system, by Agstar-2011 [5]

The study lists the many safety measures connected to the generation of biogas. The first is drowning, with ponds and liquid tanks being the most dangerous. According to OSHA requirements, there must always be ropes, ring buoys, and ladders available for use in rescue operations anytime there is a risk of drowning. The risk of drowning is greatest when the farm's equipment, particularly that near the digester or new storage tanks, is being maintained. To prevent accidental drowning, OSHA 2002 mandates that notices be displayed everywhere around storage facilities. Animals shouldn't be allowed access to this area, thus fences need to be built around it.

The other risk in a biogas plant is the possibility of major accidents brought on by falls. It is advised to perform the majority of maintenance from the ground. Elevators need to be installed when access to high terrain is required, according to OSHA's 2008A recommendation. Fall prevention measures including safety harnesses, guardrails, and self-retracting lifelines are mandatory under the OSHA 2008A regulations. These precautions must be followed if an employee is working from a height of more than 4 feet, according to the API 2006 guideline. The additional risks in biogas facilities might result from burns. Pipes carrying hot fluids or exhaust gases might result in burns. Additionally, feedstock and digestion spillage, entanglement risks, mechanical failure, and lockout present a serious threat to the workforce and the general public.

4. Issue to be analyzed

The risks associated with biogas are leakage, fire, explosion, corrosion, and exposure to the toxic compound. The bioprocess is used in the production of biogas has two phases organic and liquid. Among these two phases, the organic phase consists the volatile alkanes which are flammable, and if it gets in contact with enough ignition sources during operation or maintenance time then it can be ended in deflagration. If the relief system is not within the facilities then alkane vapors lead to pressurizing the digester in which it is formed or the tank in which it is stored. This pressurization causes blasts or explosions or sometime releases toxic gases like hydrogen sulfide, ammonia, and asphyxiant gases (a mixture of CH_4 and CO_2) in the surrounding area. The Suffocation during the unloading and cleaning operation also causes fatalities. The risk of drowning is most when workers are maintaining machinery in digesters or storage units. Potential burn dangers might exist in pipes that hold hot fluids or exhaust

fumes. Other mishaps in the production of biogas are brought on by equipment and component failures, design flaws, and improper operation or maintenance.

These all hazards come to place due to some of the irregularities in operations, lack of knowledge, and safety awareness. To create a safe environment, these should be eliminated. The proper risk assessment system needs to be there to find the possible short comes in the plant operation and help to form preventive strategies. Because of less number of documented incidents and the insufficient information, a quantitative root cause analysis is difficult.

5. Problem Analysis

The main risks related to the production of biogas are examined with the help of root causes for incidents occurred in past. The biogas synthesis is generally thought to be safer than the manufacturing of other chemicals. But It is untrue since the risk assessment matrix (included in the appendix) done based on the past events happened. The matrix indicates that it falls into the non-negligible risk category. Table 2 lists the accidents that took place at the biogas plant. There have been several mishaps involving the biogas plant up to this point; however, due to a lack of information, the following kinds of reasons might be identified: Component failures, maintenance errors, operational errors, design errors and others.

5.1 Biogas Plant Incidents

Table 2: Past biogas incidents

Incidents	Scenario	Cause	Injuries	Fatalities	Severity
France, 2016	Toxic Release	Component Failure	0	0	Incident
India, 2013	Explosion	Maintenance Error	1	2	Accident
India, 2009	Explosion	Maintenance Error	3	4	Accident
Mexico, 2009	Toxic Release	Operational Error	3	6	Accident
Germany, 2007	Explosion	Maintenance Error	2	0	Incident
Germany, 2006	Toxic Release	Equipment Failure	0	0	Incident
Germany, 2005	Toxic Release	Operational Error	12	4	Accident
US, 2004	Explosion	Maintenance Error	0	0	Incident

- ✓ Accident: Having one or more than one fatalities or severe health injuries, financial and asset losses
- ✓ Incident: Minor health injury or small disability, loss of production with asset damage

Leakage at Biogas Unit, France, 2016

The gas biogas leaked through the municipal sewage plant located at Acheres, France. The plant digested the sewage sludge in three stages. After the digestion generated biogas was taken out of the tank. And sludge was taken out from the bottom. But on the day of the incident, the bottom the malfunction of bottom valve resulted in the discharge of sludge through the bottom. The digester's vapor space was thus connected with the discharge tank of the digested sludge via the overflow pipe. The pressure alarm failed to indicate mechanical failure of the valve that results in leakage of biogas. The small amount of H₂S presented in biogas also leaked into the surrounding. Fortunately, there were no fatalities or injuries. The main cause behind this incident was the failure of the valve which comes under the category of component failure.

Biogas Tank Explosion, India, 2013

Bio Energy Pvt. Ltd dealt in the making of biogas by the anaerobic digestion process. On 15th January 2013, the biogas explosion happened. During the day of the incident, there was a leak through the outlet line of the tank. So some laborers were assigned to fix that leak. The workers totally were unaware of the gas in the tank. During drilling and welding to fix the problem at the outlet, biogas had leaked though a line that caught fire as getting the ignition source from a spark and in a moment it exploded. In that explosion, two laborers lost their lives and one was severely injured. The whole cement tank was devastated due to the explosion. There was huge asset damage. The explosion cause is due to the hot work near the tank. That comes under the category of maintenance error.

Biogas synthesis from waste water treatment, Mexico, 2009

Biogas was synthesized by anaerobic treatment of liquid sludge near the wastewater treatment plant. In 2009, the cleaning of the tank was performed by the maintenance team. While cleaning the underground tank workers came in contact with toxic asphyxiant gas from organic waste which contained methane, hydrogen sulfide, and carbon dioxide. Those gases suffocated the workers during the operation and resulted in the death of six people. Three people have been hospitalized due to heavy exposure to toxic gases led to breathing problems. The reason behind the incident was the lack of operating procedures for cleaning up the equipment. The tank was not cleaned as per the predefined period of time. Thus it comes under the category of operational error.

Biogas production from anaerobic digestion, India, 2009

The plant was being set up to waste into biogas at Aluva, Kerala, India. In 2009, 4 fatalities and 3 were injured when an anaerobic digester erupted during the plant installation. When one outlet steel pipe was being welded by a worker, an explosion occurred. The reactor was partially loaded with waste, including animal feces, during the week leading up to the disaster. In the reactor, gas was accumulating at the upper side and an explosive mixture was naturally developing. Even at a distance of thousands of feet, the explosion was audible and felt strongly. When the roof of the reactor collapsed due to the explosion, more than a dozen persons who were standing on it or nearby were injured. Three employees drowned in the slurry: Two of them died while one was only narrowly spared and later recovered. Two of the standing adjacent workers, including the welder, were killed instantaneously when the explosion hurled them away. The reason behind putting it in maintenance error is welding was performed at the digester. That welding ignited the accumulated gas through the outlet.

During the biogas production from anaerobic digestion ruptured, Germany, 2007

In Germany, 2007, A 17 meters wide and 20 meters high collapsed and spread waste around 200m of a plant. During that accident, 2 operators were severely injured and construction equipment was nearby critically damaged. A thousand liters of oil were released out of the tank. The business was just started two days before the day of the incident. The total damage to the asset was nearly around 1.5 Million Euros while the interruption loss was nearly around 1 Million Euros. The reason behind the incident was the maintenance work was going near the tank. The plant was just started so some pending work was carried out by the maintenance staff. This incident cause comes under the category of maintenance error.

During the biogas production from anaerobic digestion, Germany, 2006

In 2007, two anaerobic digesters used in biogas production burst at Gottingen. Due to bursting of two tanks, seven million liters of stored biomaterial came out in nearby area. The biomass came down from the location where the plant was built and polluted not only the manufacturing facility but also two water reservoirs. Fortunately there was not a single fatality, but the rupture of the digesters caused damage to the manufacturing unit and a storage equipment holding more than thousand of fuel oil. The total loss during that incident was nearly 10 Million Euros. The cause behind the incident was not clear but many studies concluded it was due to tank failure. Hence, the tank failure leads to Equipment failure.

H₂S Release from digestion unit, Germany, 2005

In 2005 (Germany), a large quantity of H₂S was released in a plant during the unloading waste. The huge metal doors were open because the hoist that was used to seal them had broken. There were some previous leftovers in the hole. While unloading the material a considerable amount of H₂S was released. Unfortunately, four people died because of toxic hydrogen sulfide, and twelve workers were taken to the hospital. The one major cause behind the incident was the worker's failure to comply with operating procedure and safety regulations. This put it in operational error because of lacking knowledge on how to perform the task by considering the standard procedure.

Methane Explosion, US, 2004

The biogas was manufactured through wastewater sludge. In the US in 2004, on the day of the incident, the biogas formed through a digester by fermentation of waste accumulated at top of the tank. The biogas has mainly consisted of highly flammable methane gas. After getting contacted with the ignition source it exploded and it was seen in a radius of more than 1 mile away. Fortunately, there were no fatalities or injuries to humans. The control room was damaged and the unit was temporarily shut down which caused financial loss. During the explosion, there was pending work going on at the plant that affected the digester. That indicates a maintenance error.

5.2 Root Causes

There are many possible reasons behind the incidents to the biogas manufacturing facilities shown in fishbone diagram (Fig1). Biogas release is mainly happened due to: Equipment failure, Component failure, and Operational error while Explosion is because of: Maintenance errors and Design errors. The major root causes behind the incidents are maintenance error and operational error. There are only few incidents which happened due to the equipment and component failure. The Fig 2 represents the frequencies and causes of incidents happened in past twelve years those are mentioned previously. From the investigation, It is clear that the incidents happened because of maintenance and operational error are more. Errors in maintenance procedures are performed while the plant is in operation without taking any precautions to prevent the ignition of combustible mixtures. The operational error may be to blame for a number of incidents when it was claimed that people inhaled hydrogen sulfide that was present in the raw gas.

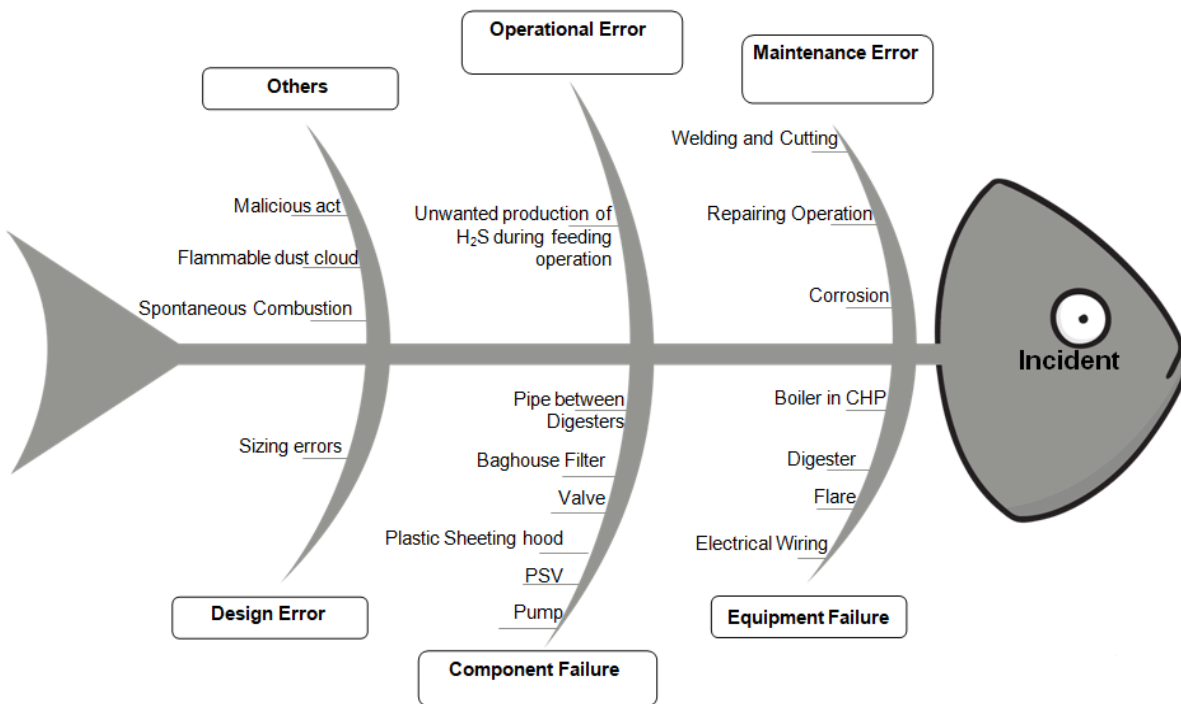


Fig 1: Fishbone Diagram of Incidents

These kinds of mishaps are common in the chemical sector, where access to units and welding activities are specifically permitted under safety regulations. To eliminate operator mistakes of this nature as much as feasible, a work permit system is often also included. More generally, better operator training and plant management understanding of risks and hazards are needed to prevent similar mishaps. The incidents because of design error, flammable dust and malicious act are very less.

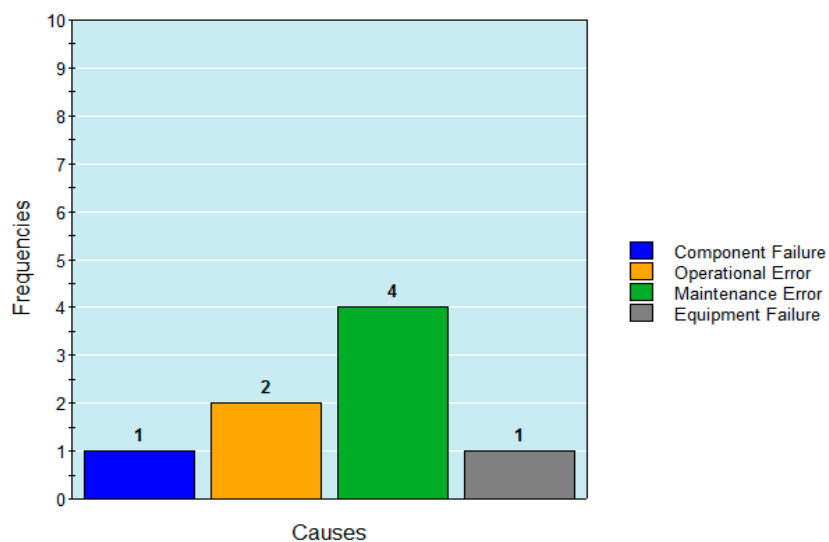


Fig 2: Type of Causes vs Frequencies of incident investigated

Biogas production falls into the category where risk cannot be avoided, according to the risk matrix (included in the appendix), which was estimated based on the incidents that occurred. In the calculation of the risk matrix, a total of 16000 biogas facilities are considered throughout the whole world during 12 year time period. By giving training to staff members on the operational procedure, work permits, and safety culture, operational and maintenance-related problems may be resolved. But to avoid the risks related to process and design, Safety measures that should be taken into account are described in Table 3.

Table 3: Safety Precautions

Equipment	Safety System
Digester and Tank	• Device against fire and explosion • Safety valve for Vacuum & Overpressure • Sluice gates: Extra gate for incase of failure
Biogas desulphurization	• Air pump for adjusting air ratio • Check valve: to avoid back flow
Flares	• Flare with arrester • Ventilation device
Condenser	• With level indicator to detect level
Digestate Tank	• Require ventilation system • Install level indicator to measure digestate
Piping	• Consist of welded section • Slope to evacuate the condensate • Pressure and corrosion resistant

6. Conclusion

In this report, the root causes of incidents help to predict the possible risks during the operation. From the analysis, we can conclude that the best way to reduce the risks is by eliminating different errors during operation. From research, it is clear that the risk related to any biogas unit is majorly due to the presence of biogas and biomaterials. The major incidents have occurred in two-phase digesters, the release of biomass or toxic gas release or explosion. Some design and operation shortcomings like a sudden rise in temperature due to pressurization, improper carbon to nitrogen ratio caused the increase in asphyxiant gases and inappropriate venting system trigger the risk of incident. From the incidents researched, the causes of past incidents are because of unclear operating procedures and maintenance work. Simplifying the procedures is a good method to reduce the probability of operational and maintenance errors. But on another side due to insufficient data on incidents, it is difficult to identify all other causes. There are no resources available publicly that help the industry identify hazards. Safety precautions steps are mentioned those are needed to be followed according to the different guidelines in different countries.

7. Recommendation

The first is the need for an ad hoc accident reporting system. It is found that numerous significant mishaps happened during unregulated maintenance procedures. These might be reduced by applying the knowledge of process safety gained from other industrial areas. To prevent design and operational mistakes, it would also be advantageous to define and implement particular safety standards for the biogas industry. It is advised to create a risk management system that can identify risks related to the introduction of both new and old technologies and give management guidance. It should be able to handle even minor variations in material purity, equipment modifications, and personnel changes that could have a major impact on the operation. In the case of personnel safety, it is needed to follow OSHA 2002 regulation which tells that signs should be displayed around the storage facility. During work, to prevent falls from high terrain elevators should be installed according to OSHA 2008A. While cleaning and doing maintenance in confined spaces or equipment like digesters, it is recommended to require a permit as per OSHA (29 CFR 1910.146). Another suggestion is to follow the guidelines on safety measures for anaerobic digestion plants for the United States: Safety Practices for On-Farm Anaerobic Digestion Systems (EPA); For Germany: Safety Rules for Biogas Systems (German Agricultural Occupational Health and Safety Agency) and Biogas: Safety First (German Biogas Association); and for France: Safety rules for agricultural biogas plants.

8. References

- [1] Casson Moreno, V. *et al.* (2016) “Analysis of accidents in biogas production and upgrading,” *Renewable Energy*, 96, pp. 1127–1134. Available at: <https://doi.org/10.1016/j.renene.2015.10.017>.
- [2] Schmid, A. *et al.* (1999) “Development of equipment and procedures for the safe operation of aerobic bacterial bioprocesses in the presence of bulk amounts of flammable organic solvents,” *Bioprocess Engineering*, 20(2), p. 91. Available at: <https://doi.org/10.1007/s004490050565>.
- [3] Casson Moreno, V., Guglielmi, D. and Cozzani, V. (2018) “Identification of critical safety barriers in biogas facilities,” *Reliability Engineering & System Safety*, 169, pp. 81–94. Available at: <https://doi.org/10.1016/j.ress.2017.07.013>.
- [4] Stolecka, K. and Rusin, A. (2021) “Potential hazards posed by biogas plants,” *Renewable and Sustainable Energy Reviews*, 135, p. 110225. Available at: <https://doi.org/10.1016/j.rser.2020.110225>.
- [5] AgSTAR, E.P.A. (2011) “Common safety practices for on-farm anaerobic digestion system.” Available at: <https://doi.org/https://www.epa.gov/agstar/safety-practices-farm-anaerobic-digestion-systems>.
- [6] Risks and safety measures for anaerobic digestion: How can you make your plant safer? (2020) BiogasWorld. Available at: <https://www.biogasworld.com/news/safety-precautions-anaerobic-digestion-systems/> (Accessed: November 29, 2022).
- [7] Risks and safety measures for anaerobic digestion: How can you make your plant safer? (2020) BiogasWorld. Available at: <https://www.biogasworld.com/news/safety-precautions-anaerobic-digestion-systems/> (Accessed: November 27, 2022).

9. Appendix

Risk Matrix						
- Period 12+ years - No. of. Plants 16000	$< 10^{-6}$ events/year	$10^{-6} - 10^{-4}$ events/year	$10^{-4} - 10^{-3}$ events/year	$10^{-3} - 10^{-1}$ events/year	$10^{-1} - 1$ events/year	> 1 events/year
Major Health effect / injury	6	2.6×10^{-5} 3.0×10^{-5} (5 events)				
Permanent disability or one fatality inside the plant						
Multiple fatalities inside the plant		2.1×10^{-5} (4 events)				
Fatalities outside the plant	None					

(No. of sites for biogas production: 16000)