Towards Safer Biogas Production

Applying Established Safety Considerations and Evaluations to Biogas Operations

An ioMosaic White Paper

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Introduction

The biogas market is growing rapidly, with a projected 4.5% CAGR from 2022 to 2027. With global and national initiatives to reduce carbon emissions such as the Paris Agreement and the UK Net Zero 2050 goal, biofuels will play a crucial role in meeting those targets. Despite their benefits, biogas facilities face significant safety challenges. Over 160 accidents have been documented from 1995 to 2014, primarily involving fires, explosions, and the release of hazardous gases.

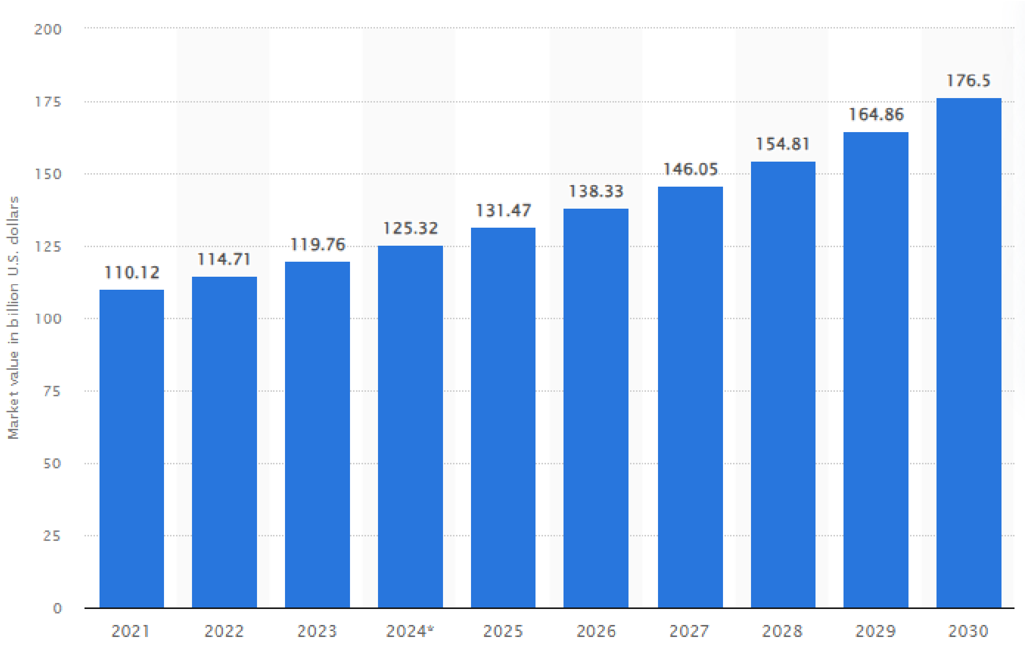
These incidents underscore the urgent need for robust safety measures in the biofuel industry. Particularly for small and medium-scale plants that fall below major accident hazard thresholds. Adopting existing chemical industry standards, such as those from API and NFPA, is essential while developing specific international regulations for biogas production. Mitigation procedures along with safeguards like emergency vents, flame arresters, and PVRVs are critical to incorporate in the design of these biogas facilities. In this white paper, the consequence from a loss of containment event was modeled to emphasize the need for established safety protocols to prevent future incidents and ensure sustainable biogas production.

Global Biofuel Production

The recent emergence of renewable fuel sources with the aim of replacing fossil fuels in the energy market has popularized the biofuel industry. The biofuel market has grown noticeably increasing by another 5.6 billion USD between 2023 to 2024 and is expected to keep growing as seen in Figure 1. The global biogas market is expected to register more than 4.5% compound annual growth rate (CAGR) from 2022 to 2027 [2]. In Europe alone, the biogas plant market was estimated at $1.87 billion in 2021, which is expected to rise to $3.47 billion by 2028 [2].

Biofuels provide carbon neutral fuel alternatives to natural gas and other crude derived fuels. They also allow production on a multitude of magnitudes, from farm scale anaerobic digestors (AD) to industrial scale bioreactors. Biofuels are a range of organically sourced fuels such as biodiesel, bioethanol, and biogas. They are derived from a range of biomass feedstocks such as food and animal waste, plant matter such as sugar cane, or vegetable and other oils.

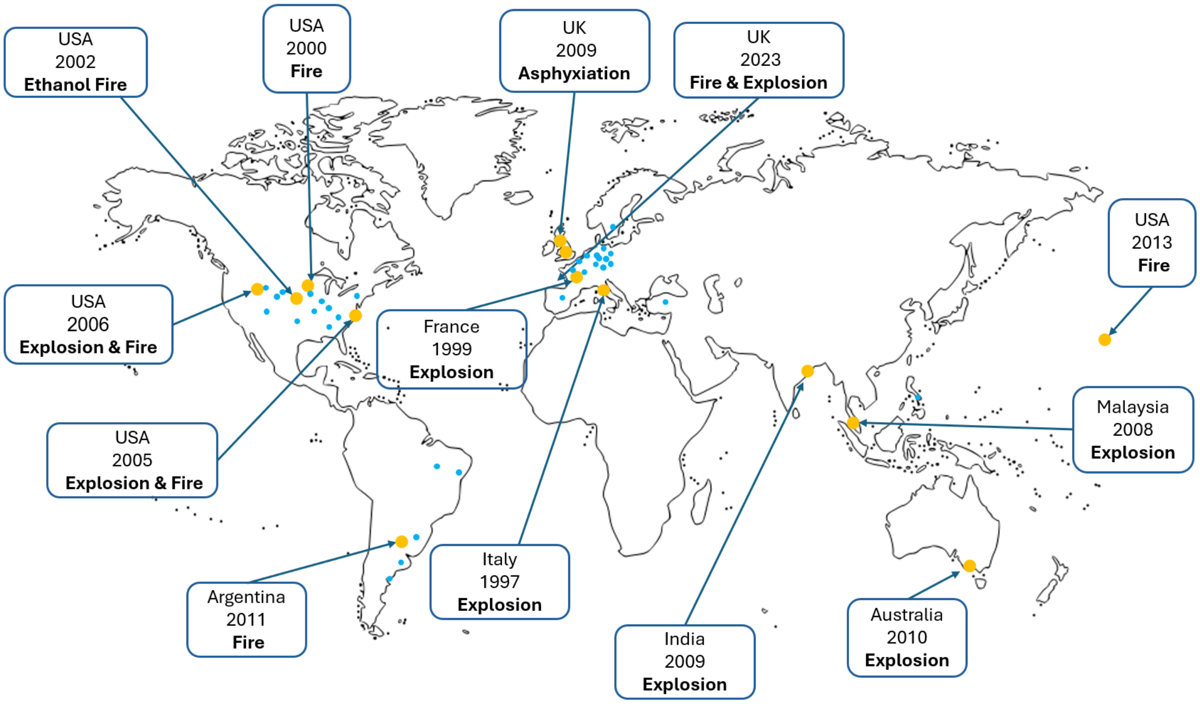
Figure 1: Market value of biofuels production worldwide from 2021 to 2023, with a forecast until 2030.



Source: Biofuels Market Size, Share & Trends Analysis Report By Application (Industrial Fuels, Transportation Fuels, Chemical Industry), By Type (Bioethanol, Biodiesel), By Region, And Segment Forecasts Till-2031 [1]

With the growth and rise in production and use of biofuels, all hazards associated with biofuel facilities, feedstocks, processes, and maintenance must be assessed and evaluated. In the biogas sector specifically, there have been over 160 accidents between 1995 and 2014, with several major incidents occurring due to unregulated maintenance work and lack of safety systems [3]. Figure 2 below shows a map of biofuel related incidents across the world.

Figure 2: World map of biofuel facility incidents [2]



Source: Casson Moreno et al., 2016. Analysis of accidents in biogas production and upgrading. [3]

Overview of Process Safety in Biofuel industry

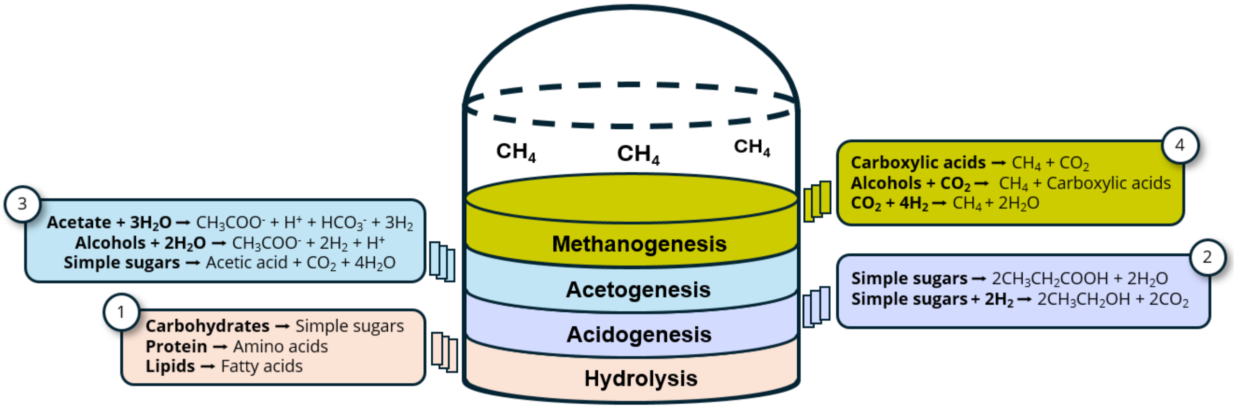
The biology behind anaerobic digestion process

The AD process is an amalgamation of intricate metabolic pathways that can generally be reduced to 4 major steps leading to methane production. Initially, the hydrolytic microorganisms are fed with rich organic matters, typically polysaccharides, proteins, or lipids, which later undergo enzymatic reactions, producing simple sugars (i.e. monosaccharides), amino acids or fatty acids [4], [5].

Sugars (alongside other organic acids in a secondary reaction) are then metabolized by other classes of microorganisms known as acidogenic bacteria to produce intermediary products such as alcohols, acetate, carboxylic acids, H_2 and CO_2 in a process called acidogenesis [4], [5]. Following this acidogenic stage, further intermediates are synthesized by acetogenic bacteria through reduction of excess organics (acetogenesis) [6].

Finalizing the AD cycle, these intermediaries subsequently form the main feedstock for methanogenic bacteria, the microorganisms that have been adapted to produce primarily methane as their metabolic byproduct (along with other gases such as H_2S, CO_2, etc.). There are two types, one being acetoclastic methanogens (e.g. *methanosarcina*) that convert acetic acid to methane and carbon dioxide, and hydrogenotrophic methanogens (e.g. *methanobacterium*) that reduce CO_2 in the presence of hydrogen to yield methane and water [4]. Figure 3 describes a simplified AD process.

Figure 3: Steps to scaling up biogas production at the molecular level [4], [5] and [6], which include (1) Hydrolysis, (2) Acidogenesis, (3) Acetogenesis and (4) Methanogenesis stages



Source: ioMosaic Corporation

Biogas production

Biogas production can range from micro modular mobile AD systems used domestically to large-scale industrial biogas plants. As of 2023, there are approximately 50 million micro-scale AD and 132,000 small, medium, and large-scale digesters globally [7]. The United States has approximately 2,300 anaerobic digesters, 331 manure-based primarily located on dairy, pig, poultry, and beef farms [7]. In 2015, Europe has 17,400 AD systems, producing 18 billion cubic meters of renewable methane gas, which is equivalent to 18 trillion liters of biogas [7]. These methods are a viable way of generating biogas from waste – however, their technologies, safety features, complexity, and equipment involved varies according to the design.

Small-scale production

Small-scale biogas production is becoming increasingly popular throughout the UK due to its small footprint, ease of use, quick installation period, and ability to reduce energy and waste disposal costs [8]. Additionally, it lowers carbon emissions and decreases the amount of organic waste sent to landfills, making small-scale anaerobic digesters a practical choice for farmers across the UK [8].

Small AD systems used in farms use simple technology, where waste (in slurry form) is fed into a shipping container and is digested by the bacteria to produce biogas and a by-product of slurry to be used as crop fertilizers [8].

Additionally, smaller-scale anaerobic digesters can be installed in homes, using similar technology to digest household food waste [9]. The biogas produced can be used directly in gas stoves for cooking, making it a cost-effective, low-maintenance alternative method for obtaining fuel [9].

Large-scale production

Large-scale production of biogas can be complex. Unlike small-scale AD, large-scale bioreactors require precise control of environmental factors to ensure maximum biogas yield and safe operation. There are numerous types of commercial biogas plants depending on the capacity and function of the facility. Table 1 highlights the different types of commercial biogas plant.

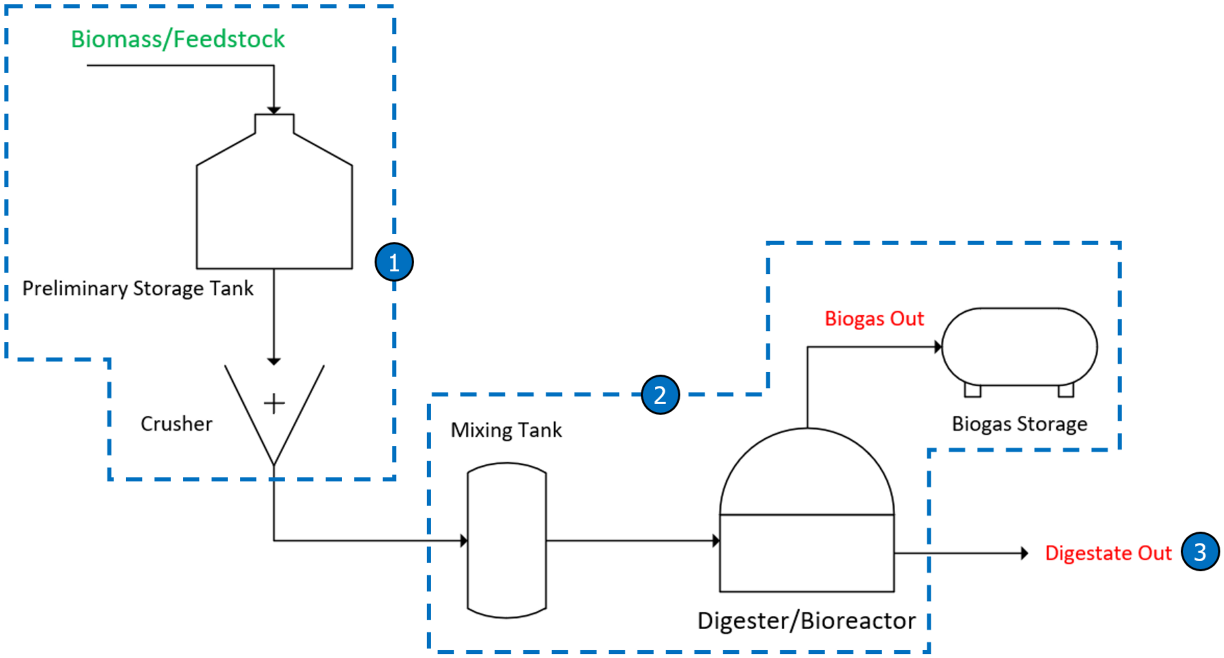
Table 1: Types of commercial biogas plants [10]

Type	Description
Batch	▪ Digester is fully loaded, sealed, and allowed sufficient time to complete the decomposition process ▪ Useful when supply of feedstock is irregular to maintain continuous production, and is well suited for feeds with very high % of dry matter ▪ Could get uneven gas generation due to the nature of the bacteria digestion process
Continuous	▪ Digester is fed regularly with feedstock to produce a continuous stream of biogas ▪ Can come in two sizes: single-stage or double-stage ▪ Double-stage biogas plants have a better yield of biogas – which is more suitable for large, more complex facilities
Floating Dome	▪ Digester has an intake of slurry and an outlet for digested slurry removal ▪ Biogas produced is stored in a movable gasholder inverted over the slurry ▪ The gasholder moves up and down to maintain pressure inside the digester

Process of Biogas Generation

Biogas is generated through a multi-stage process as seen in Figure 4 below.

Figure 4: Simplified process flow diagram of biogas production



Source: ioMosaic Corporation

1. Feedstock pretreatment

   A diverse range of materials can be used as feedstock in the biofuel industry. These are delivered to the plant in liquid-slurry or dry form.

   Choosing the right feedstock is important as what is fed into the digester determines the quality and yield of the biogas produced. A reliable feedstock supply is fundamental to the profitability of the AD. Moreover, feedstocks are not as regulated compared to chemical facilities producing special chemicals. The rate of biogas production in the digesters can be hard to predict and model due to the complicated metabolic pathways of the microorganisms during decomposition reactions. The yield of biogas from a feedstock can vary due to the following factors [11]:

   - Dry matter content
   - Energy left in the feedstock
   - Microbial species used for AD
   - Cell deaths
   - Residence time in the digester
   - Type of AD plant and conditions in the digester
   - Purity of the feedstock

The feedstock shall undergo pre-treatment depending on its state when delivered. Substances that could hinder the decomposition process, such as non-biodegradable packaging, metal, and grit, will be discarded [10]. Next, the biomass is sanitized before entering the digester.

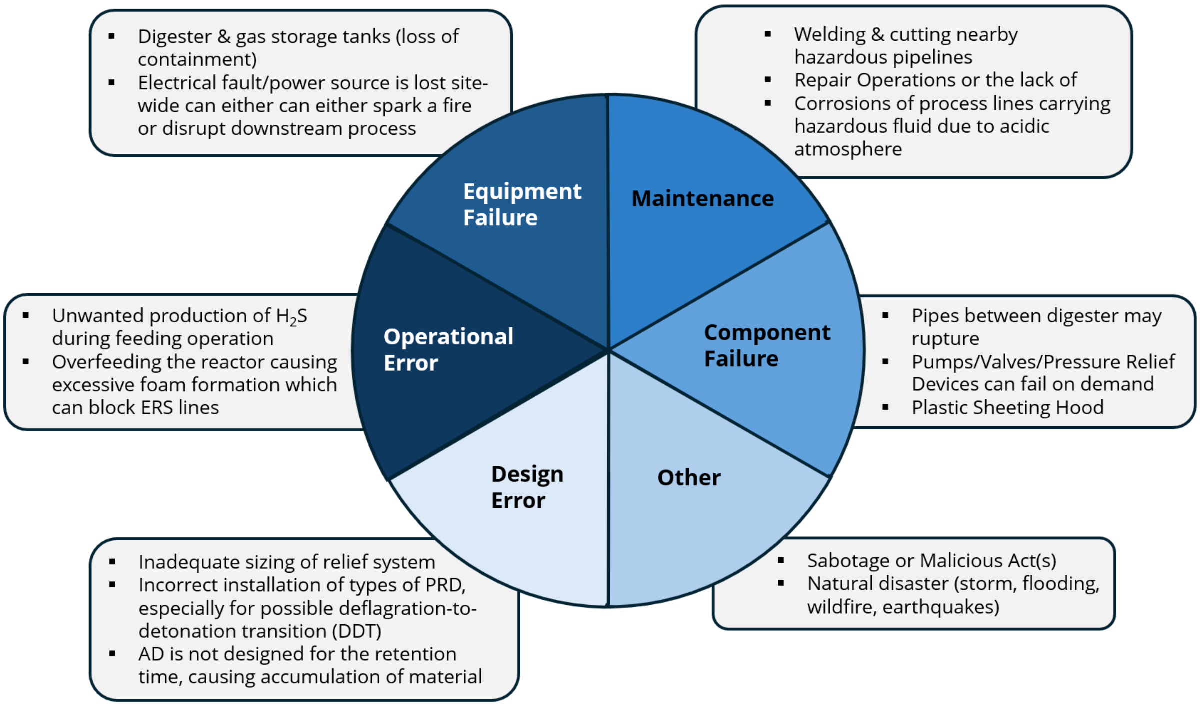
2. Biogas generation in the reactor
   The biomass slurry undergoes fermentation and is broken down by microbes in a moist environment and in the absence of oxygen. This reaction releases biogas, which is a mixture of methane and CO_2. The biogas is collected in a gas tank from the top of the biogas reactors [12].

3. Digestate utilized as fertilizers
   The digestate is the residual solids and liquids produced during biogas production. This is fed into a post-digester reactor and then to storage tanks [12].

Incidents in biogas production

Over 160 incidents related to the biogas supply chain occurred from the year 1995 to 2014 [3]. From the period of 2007-2011, the number of accidents in the biogas sector increased more than five times, surpassing the rate of biogas installations during the same period [3]. These incidents are primarily linked to fire, explosion, and the release of raw biogas from the digester, which contains hydrogen sulfide [3]. However, incidents involving access to confined spaces that result in asphyxiation are also reported [3]. A list of past incidents that have occurred in the biogas industry can be found in Appendix A and Figure 5 summarizes the causes of past incidents.

Figure 5: Main causes of past incidents in biogas plants



- Digester & gas storage tanks (loss of containment)
- Electrical fault/power source is lost site-wide can either can either spark a fire or disrupt downstream process

- Welding & cutting nearby hazardous pipelines
- Repair Operations or the lack of
- Corrosions of process lines carrying hazardous fluid due to acidic atmosphere

- Unwanted production of H_2S during feeding operation
- Overfeeding the reactor causing excessive foam formation which can block ERS lines

- Pipes between digester may rupture
- Pumps/Valves/Pressure Relief Devices can fail on demand
- Plastic Sheeting Hood

- Inadequate sizing of relief system
- Incorrect installation of types of PRD, especially for possible deflagration-to-detonation transition (DDT)
- AD is not designed for the retention time, causing accumulation of material

- Sabotage or Malicious Act(s)
- Natural disaster (storm, flooding, wildfire, earthquakes)

Source: Adapted from ‘Analysis of accidents in biogas production and upgrading’ by Moreno et al (2016)

Codes and Standards for the biofuel industry

Despite the widespread installation of biogas plants, the safety of these facilities have not been specifically addressed to date [3]. There is a lack of dedicated safety standards aimed at controlling the hazards and risks associated with biogas production and scale-up because most biogas production plants are small or medium-scale, falling short of the thresholds for legislation aimed at controlling major accident hazards, such as the Seveso Directive [3]. Recent studies in the literature exploring biogas safety issues indicate the necessity for specific and harmonized international standards for biogas production and upgrading [3].

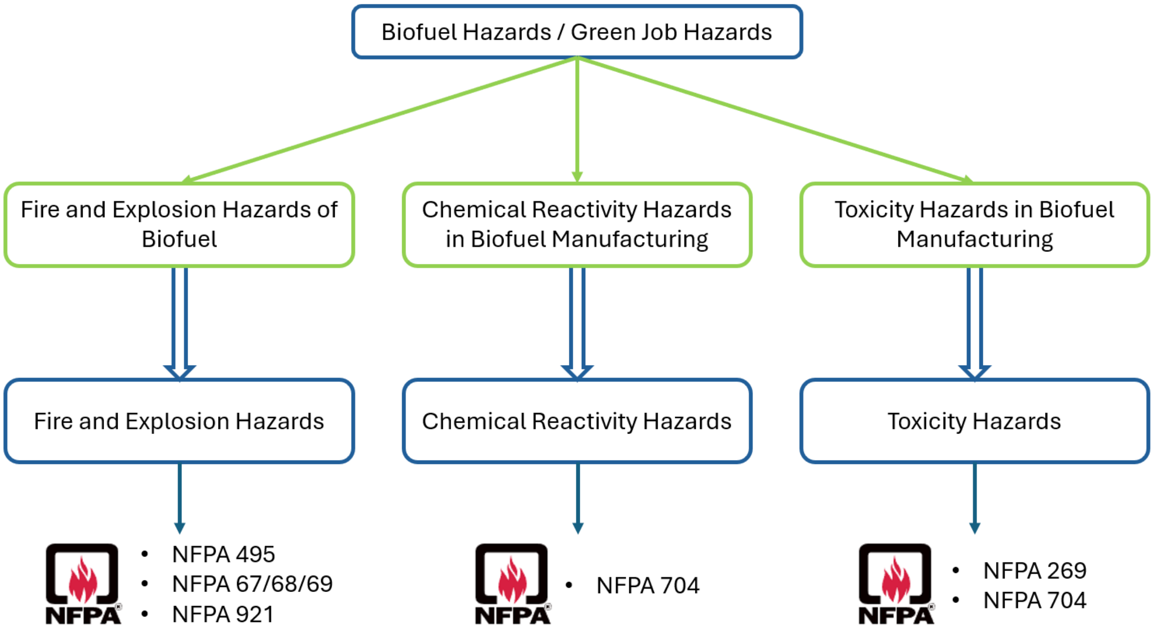
The UK has its own sets of regulations regarding biogas productions, primarily aimed at the scales of the premises and the extent of activities it authorizes. Small premises such as farms or public services (hotels, hospitals, etc.), granted that no more than 1250 m^3 of feedstock is processed in a digester at any given time, are bound by the T24/T25 Exemptions Permit. Standard Permits are also made available for organizations (e.g. manufacturers) who wish to upscale their biogas facilities. This permit is granted upon compliance with the SR2012 No.12 Statutory Guidance, which vaguely briefed operators on the needs of pressure safety devices and auxiliaries within a biogas production plant. Nonetheless, the latter regulations often place a much wider focal point on safe & sustainable agricultural practices and also disease control & prevention efforts, eluding from the fact that hazards from methane production can be as devastating.

With the prevalence of biofuel facilities globally, regulatory bodies are responsible for creating relevant and specific design standards, codes of practice and other safety-oriented regulations for these systems. However, existing regulations governing the chemical industry already exist and could be applied, such as the API and NFPA standards. For example, NFPA 68/69 contain general design standards for explosion protection, which is a common consequence of chemical and biofuel systems, as discussed previously. Similarly, NFPA 497 is recommended practice for handling flammable liquids and vapors alongside electrical installations in chemical process areas. Methane being a frequently present, volatile vapor in biogas facilities [13], means existing standards such as NFPA 497 are applicable and could be used during the plant and systems design to minimize risk.

This perspective is outlined in OSHA's biofuel specific hazards advice [14]. Their approach is similar, as they identify the hazards associated with biofuel facilities, such as fires and explosions due to unexpected ignition, and link them directly to existing regulations, such as NFPA 68/69. This is illustrated in Figure 6.

As there is a significant overlap of hazards between biofuel and chemical systems, the established standards like API and NFPA can be used as steppingstones towards safer biofuel production until biofuel specific regulations are put in place.

Figure 6: Illustrative flowchart of biofuel hazards associated with chemical hazards and standards from OSHA



Source: ioMosaic Corporation

Mitigation

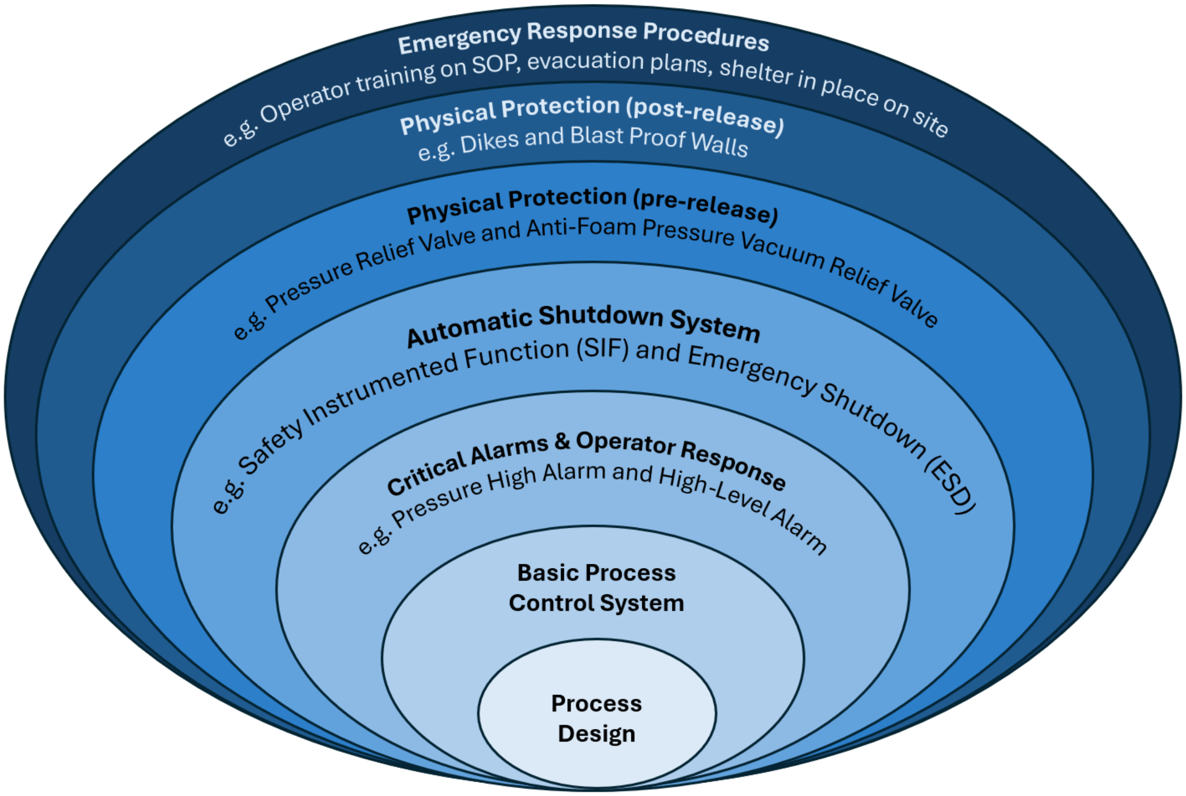
Methodologies to improve biogas facility safety

Mitigation plays a crucial role in all process facilities to proactively prevent accidents. ioMosaic recommends that all facilities to prioritize the following procedure to enhance system safety:

1. Understand the potential hazards through HAZOP and HAZID studies and conducting external audits of the facility
2. Conduct testing to understand the components used in the process and their associated hazards, such as worst-case feedstocks and the gases produced
3. Understand the consequences (e.g. explosion, fires, and dispersion) through modelling and conduct a facility siting to carry out Quantitative Risk Assessment (QRA) of the plant
4. Conduct LOPA study to determine how many independent protection layers are needed to fall within the tolerable risk of the company (see Figure 7 for an example LOPA of a biogas facility). This may include installing safeguards (as seen in Table 2), alarms, and process controls.

5. Perform sizing for the installed relief devices as the last layer of protection, including the placement of the vent and flame arresters which is key due to the potential of flame acceleration in elongated geometries.
6. Design the facility according to the studies conducted previously
7. Implement administrative controls under Process Safety Management (PSM), focusing on the common hazards in biogas industries

Figure 7: Example LOPA of a biogas facility

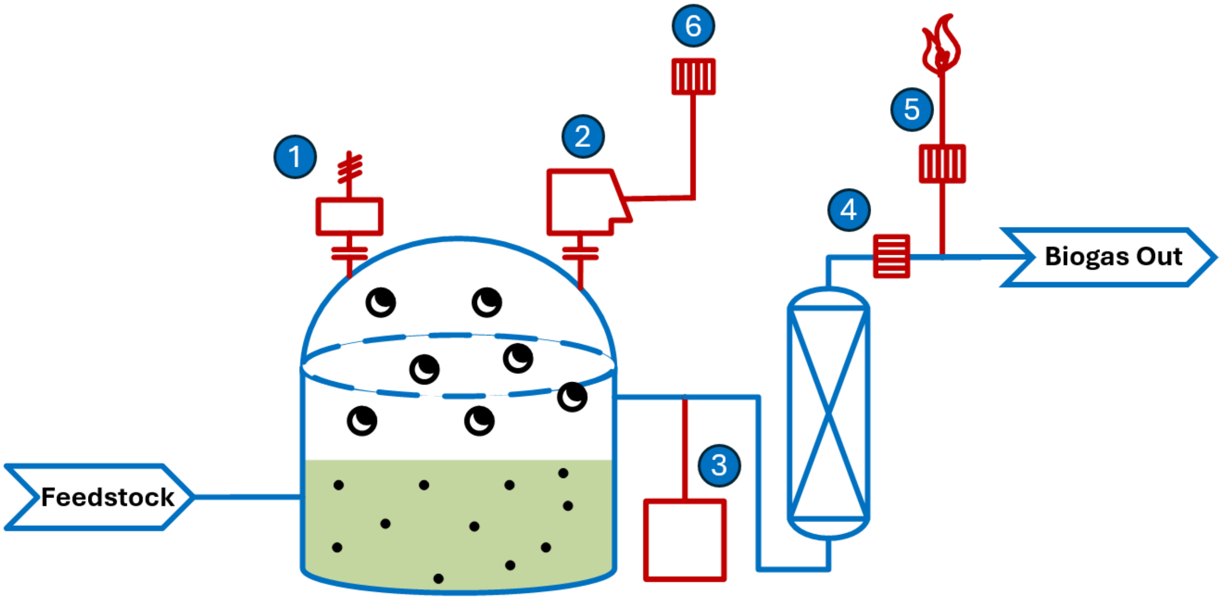


Source: ioMosaic Corporation

Mitigation Strategies

The following schematic shown in Figure 8 is a simplified representation of a biodigester in a biogas facility with typical safeguards installed. Table 2 contains the descriptions and purpose of these safeguards.

Figure 8: Simplified schematic of a typical biodigester and possible safeguards (in red)



Source: ioMosaic Corporation

Table 2: Examples of safeguards that can be installed into a biogas facility

No.	Equipment	Purpose and Comments
1	Emergency Vent	Last line of defense – emergency vent should open during an overpressure event caused by fire
2	Anti-foaming Pressure Vacuum Relief Valve (PVRV)	▪ Foam is prevalent in biogas facilities due to the micro-organisms in the bioreactor producing gas, resulting in micro-organisms suspended in the foam ▪ These foams are typically problematic as they could block overpressure protection system – making them inefficient for use ▪ Bioreactors are generally operated at low pressures and the vessel is at lower design pressure, therefore a PVRV is essential for inbreathing or outbreathing scenarios ▪ The geometry of the PVRV is important to prevent blockage in the inlet ▪ Design of the nozzle into the PVRV should incorporate anti-foaming properties, utilizing a complex and compact design to dampen and prevent the foam from entering the moving parts of the valve
3	Condensation Trap	Remove lower volatile components, such as water, that are carried out of the AD. This helps prevent liquid carryover, which can cause operational issues in the downstream gas systems.
4	In-Line Flame Arrester	With a flare installed in the system, there is a risk of deflagration as the system is filled with methane. Using current data, the flame arrester gap can be determined based on the flame speeds already known in literature. A flame arrester should be installed to ensure the flame does not travel back into the bioreactor, causing an explosion and fire.
5	Flare	A flare system is essential if there are fluctuations in gas production due to the varying feedstock used for the bioreactor. The flare can handle the surges in gas production to flare off the excess gas produced to avoid overpressure in the downstream system.
6	End-of-line Flame Arrester	This is similar to the in-line flame arrester – however, end-of-line arresters are placed at the outlet piping leading to the atmosphere to offer protection against atmospheric explosions entering the process

Apart from safeguards, there are several other factors that should be considered to mitigate accidents occurring in the biogas facility. These include, but are not limited to:

- Installing leak detection systems
- Ensure non-combustible components are around the facility
- Operator training on Standard Operating Procedures (SOP) (i.e. to prevent hot works during operation)
- Ensure the facility is in a well-ventilated area
- Establish a safe procedure for commissioning and start-up/shut-down process
- Provide backup power supply for mixing in the bioreactor

Deflagration

As established in previous sections of this white paper, flammable gases can be produced within biogas production equipment. It is possible to have an adequate amount of oxygen in the process equipment and a heat source present in the system. This could lead to deflagrations within the system.

To prevent catastrophic failures, explosion venting, also known as deflagration venting, is employed. This method helps manage the pressure inside vessels or enclosures by allowing controlled release of gases. Simplified equations, such as those found in NFPA 68, are commonly used to determine the requirements for deflagration relief. While these equations are user-friendly, they often overestimate the relief needs and have several practical limitations.

Simplified equations for deflagration venting are typically designed for ideal geometries such as hoppers and short vent lines. However, they may not be applicable for complex geometries, with elevated initial pressures and temperatures and geometries with long length-to-diameter (L/D) ratios, or geometries with extensive vent piping where flame acceleration becomes significant.

To address these limitations, ioMosaic have developed detailed deflagration and explosion dynamics methods and computer codes. These advanced methods offer a more accurate representation of combustion reactions using direct Gibbs free energy minimization coupled with a detailed burning rate model following the equation below which is valid for non-elongated geometries:

$$S_f = (\chi + \eta) S_{u0} \left[\frac{T_u}{T_o}\right]^{\alpha} \left[\frac{P}{P_o}\right]^{\beta}$$

S_f: Laminar flame speed, S_{u0} initial/reference Laminar flame speed, T_u Temperature of the system, P is the pressure of the system, P_o is the reference pressure, T_o is the reference temperature, α is the temperature exponent, β is the pressure exponent. χ is a turbulence factor which accounts for vent opening dynamics. and η considers the increase in flame surface area due to cell formation.

A one-dimensional fluid dynamics model has been developed in SuperChems™ to present an example of how deflagration dynamics can be predicted within simple geometries (rectangular, cubic and spherical). One-dimensional fluid dynamics model is one tool integrated into Process Safety Office® SuperChems™ that is useful in analyzing flame accelerations and reflections to improve the design and placement of blast discs (rupture discs) and deflagration or detonation-type flame arresters. Numerous empirical and semi-empirical correlations for flame acceleration in pipes have been documented in the literature, often relating flame acceleration to the L/D ratio. One such correlation for ducts or pipes without obstructions (smooth pipes), based on measured flame acceleration data for gases such as hydrogen, methane, propane, and ethylene, is:

$$\frac{S_f(x)}{S_u} = 6.5\sigma \exp\left[0.0061(\sigma - 1)(1 + 15BR)\left(\frac{x}{D}\right)\left(\frac{D}{0.15}\right)^{0.4}\right]$$

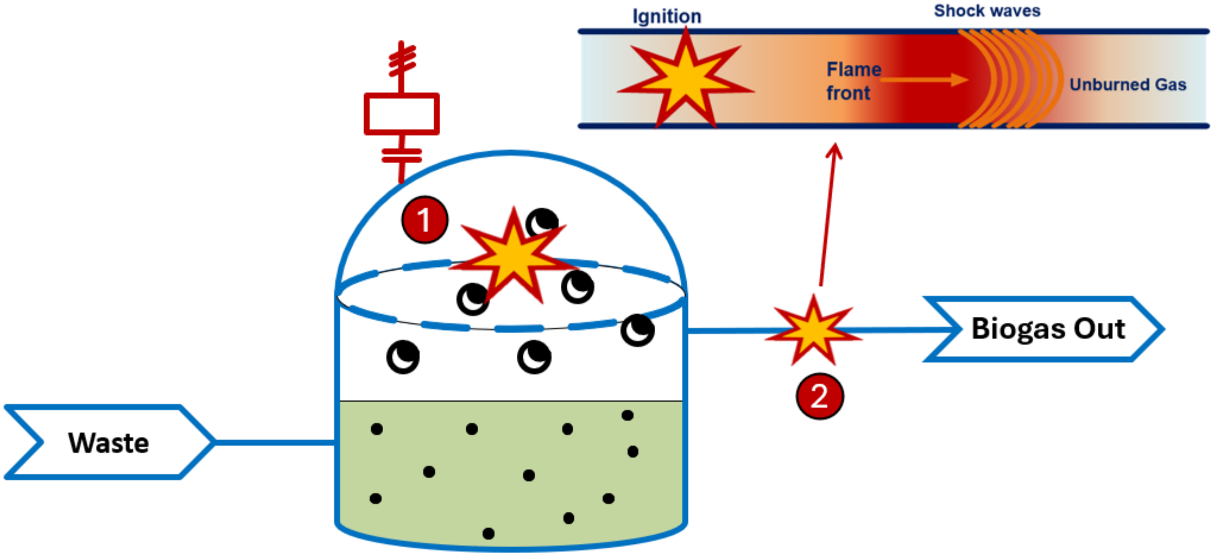
$S_f(x)$: Laminar flame speed across axial distance "x", S_u initial/reference Laminar flame peed, D is the pipe diameter, x is the distance/position along the piping. BR is the blockage ratio, σ is the expansion ratio.

In relation to the deflagration model, the non-ideal behavior of burnt and unburnt gaseous components would have been accounted for during combustion and venting. Detailed chemical equilibrium calculations had been incorporated at every time step to represent the stoichiometry of the reactions as temperature and pressure change in the explosion volume.

Following vessel deflagration, ignition risks and possible air ingress is present if the biogas is transferred to a combined heat and power (CHP) system. This could lead to further deflagration in the piping, which may then accelerate to detonation (DDT), generating high overpressures. For elongated geometries such as process piping of the biogas production system, flame acceleration due to flow turbulence and the presence of obstructions can result in much higher burning velocities.

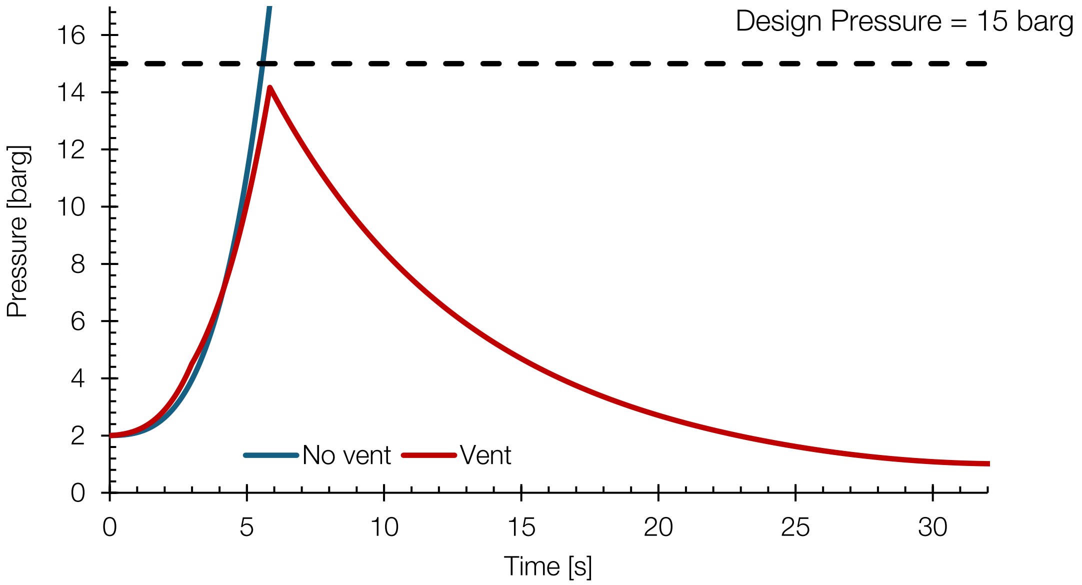
The schematic below will be used as the basis to explore the consequences of deflagration within the vapor space of an AD and within the outlet piping containing biogas (see Figure 9).

Figure 9: Deflagrations locations that could occur: (1) spherical deflagration in AD vapor space and (2) elongated deflagration in biogas outlet piping



Source: ioMosaic Corporation

Figure 10: Spherical deflagration in AD and effect of vent installation in mitigating overpressure in vessels

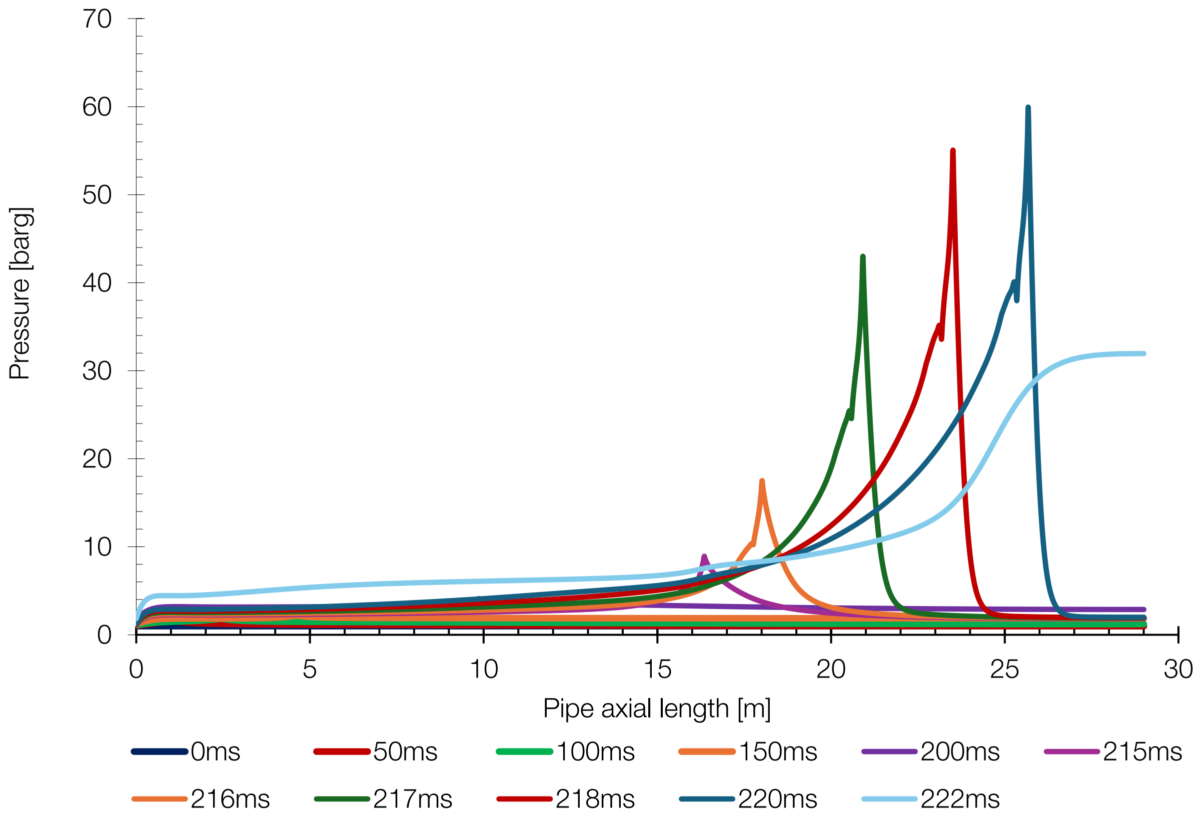


Source: ioMosaic Corporation

Installing emergency vents on process equipment is paramount in mitigating against overpressure due to deflagration. Figure 10 illustrates the pressure profile inside an AD when deflagration occurs in absence of a vent (blue) and when a vent is installed (red line). Without a proper relief line, the pressure inside the AD increases exponentially and will eventually overpressure the vessel and possibly detonate. However, with adequate venting, as the set pressure of the emergency vent is reached the vent will open and depressurize the vessel, preventing further accumulation.

Figure 11 below is for a low concentration of methane present in the pipeline with air. Multiple snapshots of the pressure propagation at different time stamps are displayed. As the time increases, the pressure waves increase in magnitude and the flame front accelerates through the pipe. This would result in the pipes rupturing and damaging piping supports, causing further loss of containment or hydraulic explosions.

Figure 11: Elongated deflagration in pipeline at different time stamps

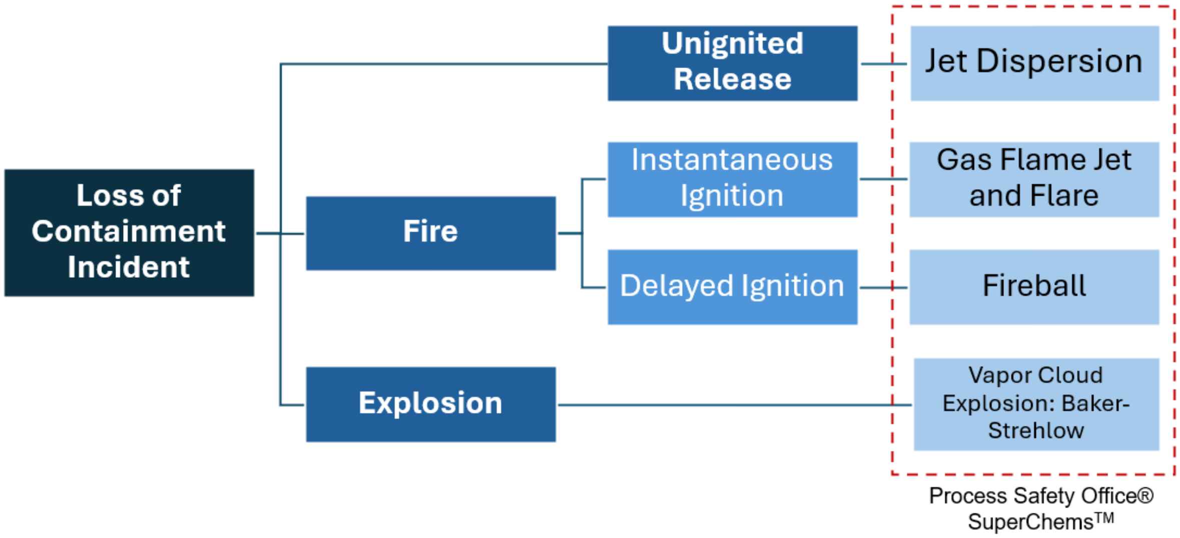


Source: ioMosaic Corporation

Process Safety Modeling of Biogas Facilities

Following the mitigation strategies and general methodologies to improve biogas facility safety, the consequences from a loss of containment (LOC) event was further investigated as seen in Figure 12. Examples of process safety modeling were conducted in Process Safety Office® SuperChems™ to demonstrate the applicability and useful information that can be obtained for safer equipment and emergency relief system design.

Figure 12: Loss of containment incident flowchart



Source: ioMosaic Corporation

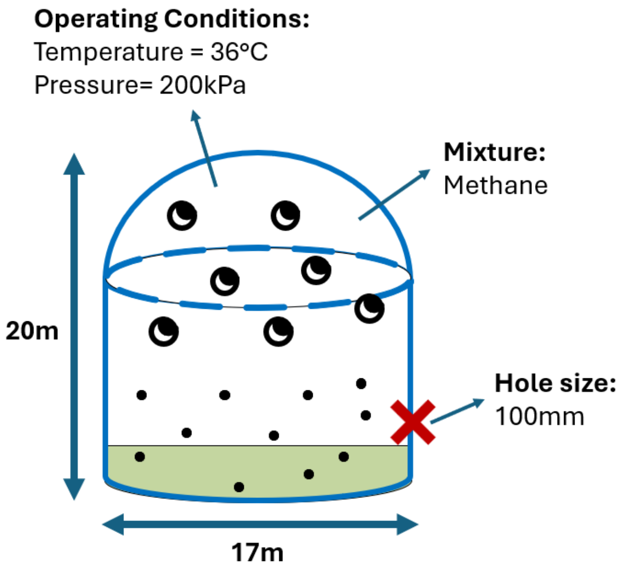
In this example, a 20m high and 17m wide biogas storage dome at a wastewater treatment plant was modelled as seen in Figure 13 (dimensions based on a case study in Germany 2007 - Appendix A). From the case study, the operating conditions are not known.

Most AD processes at wastewater treatment plants operate within the mesophilic range [15]. It is crucial for operators to keep temperatures within a narrow band, typically between 35°C and 37°C [15]. Therefore, for the purpose of modeling the biodigester, the operating temperature will be 36°C. The operating pressure is 200 kPa as this is the typical operating pressure inside a biogas storage dome [16].

Biogas produced in the biodigester typically consists of methane (50-75%), CO_2 (25-50%), water (H2O), nitrogen, oxygen, hydrogen sulfide, ammonia, and trace elements (organo-halogenated, siloxanes, etc.) [15]. However, the biogas composition varies according to the feedstock [15]. For the purposes of modelling a loss of containment scenario from the biodigester, pure methane will be used.

The hole size used to model the LOC scenario is 100 mm, which is a typical hole size according to API RP 581 [17]. The location of the loss of containment was assumed to be at the bottom of the tank, above the liquid level i.e. the liquid loss of containment is not modelled.

Figure 13: Biodigester set up that is used for consequence modeling (not to scale)



Source: ioMosaic Corporation

Dispersion

During a LOC event – the biogas accumulated in the tank will disperse to the surroundings. If the tank is in a confined location – the personnel in the nearby area may be subjected to asphyxiation. Currently, there are no specified occupational exposure limits for methane gas [18]. However, the National Institute for Occupational Safety and Health (NIOSH) in the United States recommends a maximum concentration of 1000 ppm (0.1%) over an eight-hour work period [18]. Therefore, the exposure level (ppm) of methane (lower and upper limit) can be seen in Table 3.

Table 3: Exposure level [ppm] used in dispersion modelling for methane and biogas mixture

	Exposure Level [ppm]	Effects or Symptoms
Methane	1,000	NIOSH 8-hours Threshold Limit Value
	500,000	Asphyxiation

However, in this example, the biogas tank that was modeled is not in confinement. Therefore, the risk of asphyxiation was not considered as the compounds are neither toxic and/or had accumulated in a confined space. Moreover, methane is less dense than air hence as a result of LOC, methane would disperse, traversing immediately above atmosphere and shall remain buoyant.

Instantaneous and Delayed Ignition

Methane is a highly flammable gas, therefore when an ignition source is present an instantaneous and/or delayed ignition could occur. For modelling purposes, a receptor height was assumed to be 1.8 m as this is the height where personnels will be operating on the plant.

Instantaneous Ignition

In this example, the biogas tank is a low-pressure tank, therefore a sustained jet fire is not likely to occur. Therefore, this consequence was not modeled as part of this white paper.

Delayed Ignition

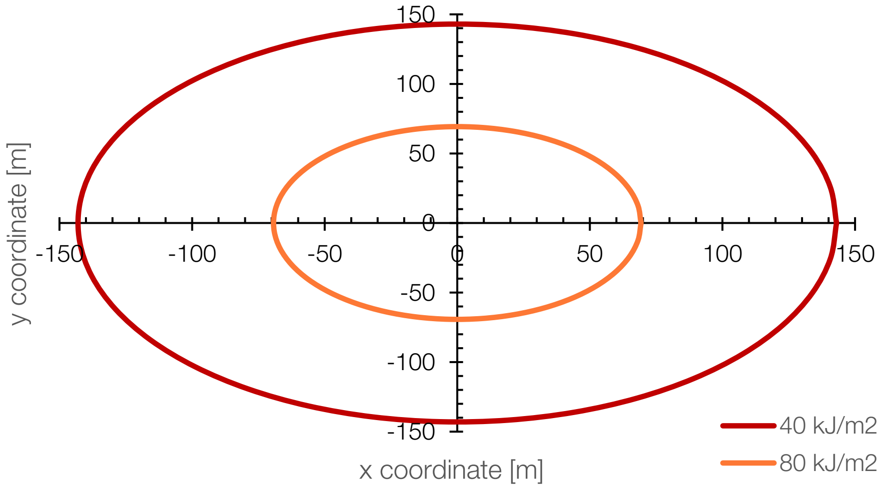
The thresholds for heat transfer rates for a fireball is displayed in Table 4.

Table 4: Heat transfer rate for fireball thresholds [19]

Heat Transfer Rate for Fireball [kJ/m^2]	Description
40	Pain or mild second-degree burns
80	Severe second-degree burn that may lead to potential injury
160	Severed third-degree burns that will result in permanent injury

Figure 14 displays the heat transfer rate for a methane fireball from a 100mm hole size. The maximum heat transfer rate for a fireball is 80 kJ/m^2. This implies that the consequence of a delayed ignition could potentially cause severe second-degree burn that may lead to potential injury to humans.

Figure 14: Fireball for methane with 100mm hole size



Source: ioMosaic Corporation

Vapor Cloud Explosion

During a loss of containment event, the methane from the biodigester is released to the atmosphere – this is known as a vapor cloud. If present in sufficient quantities, the methane will mix with air and cause an ignition and explode, producing a blast wave which can cause major destruction at large distances [20].

The thresholds that will be used to assess the effect of overpressure to buildings are tabulated in Table 5.

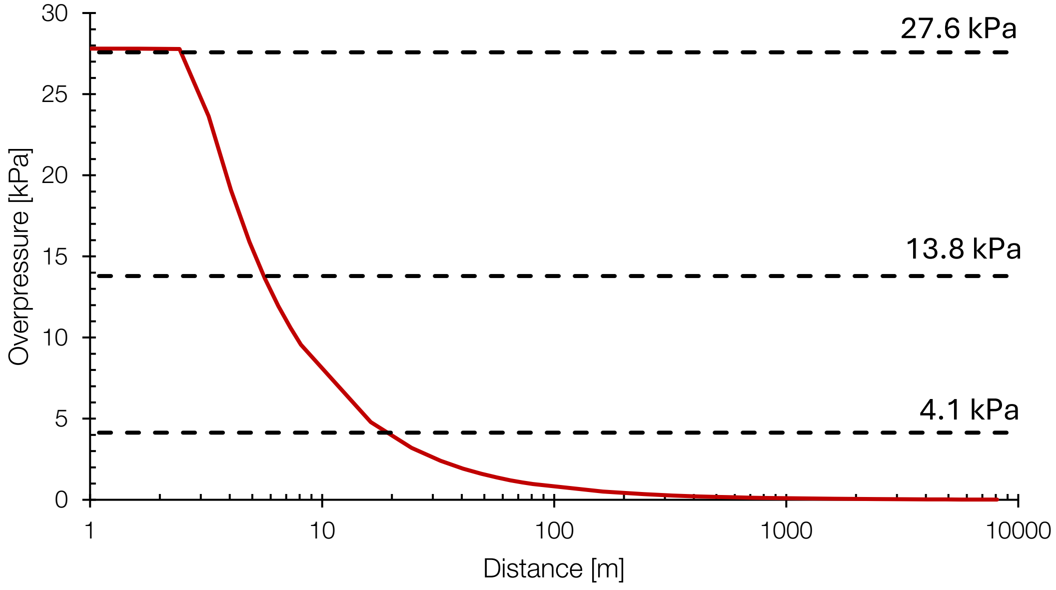
Table 5: Overpressure thresholds [21]

Overpressure [kPa]	Description
4.1	Large and small windows usually shattered; occasional damage to window frames
13.8	Partial collapse of walls and roofs of buildings
27.6	Frameless, self-framing steel panel building demolished.

	Cladding of light industrial buildings ruptured and rupture of oil storage tanks.
41.4	Nearly complete destruction of buildings

Figure 15 displays the consequence from a VCE from a loss of containment of methane through a 100mm hole size. The consequence reaches a maximum of 27.8 kPa at 0.8m from the source of the LOC.

Figure 15: VCE from loss of containment of methane from a 100mm hole size



Source: ioMosaic Corporation

Conclusion

With global initiatives like the Paris Agreement and the UK's Net Zero 2050 goal driving the reduction of carbon emissions, biofuels have become crucial in the transition to renewable energy. The biofuel market, particularly biogas, has experienced significant growth, with the global biogas market projected to register a 4.5% CAGR from 2022 to 2027. Despite their environmental benefits and potential to be an alternative to fossil fuels, biogas facilities face substantial safety challenges that must be addressed to ensure sustainable development.

The safety risks associated with biogas production, highlighted by over 160 accidents between 1995 to 2014, epitomizes the urgent need for robust safety measures, particularly for small and medium-scale plants that fall below the major accident hazard thresholds. These incidents are primarily linked to fire, explosion, and the release of raw biogas from the digester, which contains asphyxiants such as hydrogen sulfide and CO_2. Adopting existing chemical industry standards, such as those from API and NFPA, as interim guidelines while developing specific international regulations for biogas production is essential. Safeguards such as emergency vents, flame arresters and PVRV are also necessary in biogas facilities as the final line of defense to protect against overpressure scenario resulting in deflagration and/or detonation.

LOC scenarios were also modelled using Process Safety Office® SuperChems™ to investigate the consequences of dispersion, VCE, instantaneous and delayed ignition of methane from a biogas tank. Since the storage tank in the example is not in confinement, risk of asphyxiation was not considered as the compounds are neither toxic and/or had accumulated in a confined space. Methane is buoyant; therefore, it would disperse quickly after release. A sustained jet fire is also not likely to occur due to the tank being low-pressure. For delayed ignition, a fireball with 80 kJ/m^2 heat transfer rate can be felt up to 69m (in x and y direction) from the LOC location. A VCE could occur from LOC of methane through a 100mm hole size, which reached a maximum of 27.8 kPa at 0.8m from the source of LOC.

Without an established code and standards specific to the biogas industry, incidents will continue to occur in biogas facilities, especially in the absence of robust mitigation strategies. Therefore, adapting the existing standards and implementing the methodologies to improve biogas facility's safety, as evidenced in this study, is crucial in preventing future incidents from occurring.

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Appendices

Appendix A: Example of past incidents in the biogas industry [3], [22] and [23]

Location, Year	Incident Type	Description
Italy, 1997	Explosion	An explosion occurred during repair work on a digester used for biogas fermentation and production. The blast was caused by a gas leak and welding residues. Two workers were thrown out and killed, while a third fell to the bottom of the building and was seriously injured. The tank roof was also ejected.
France, 1999	Explosion	Biogas production from the AD of paper mill waste, an explosion equivalent to 5 kg of TNT destroyed a gasometer and the pipeline to the CHP/flare. The inlet to the gasometer was blocked, causing low pressure that allowed air to enter through Teflon joints, forming an explosive mixture that was ignited by the flare's pilot flame. Damage to surrounding buildings was observed within a 130m radius. The accidental production of hydrogen in the digester was also investigated as a potential cause of the accident.
USA, 2004	Explosion	A methane explosion occurred in the control room of a sewage treatment plant due to methane accumulation from raw sewage in the building. The explosion was seen more than 1.5km away but the ignition source is unknown. There were no victims, but the control room was destroyed and the plant was temporarily bypassed.
Germany, 2007	Explosion	A 20m high and 17m wide fermenter ruptured in a biogas plant in Daugendorf after two days of operation, however, the cause is unknown. The biomass in the fermenter spread up to 200m around the plant. Some construction equipment was damaged and buildings near the fermenter were partially destroyed.
UK, 2009	Asphyxiation	During biogas production from AD, a worker attempted to loosen a crust that was obstructing the digester's operation. He died after inhaling the gas inside the digester.
India, 2009	Explosion	A large masonry and RCC anaerobic digester in Edathala Panchayat Ernakulam District exploded during its commissioning stage, killing four people and injuring three. In the week leading up to the accident, the reactor had been partially charged for trial operations with animal dung and other waste. This led to gas accumulation and formation of an explosive mixture in the reactor's upper space. The explosion occurred when a welder was heating or welding an outlet steel pipe and was felt and heard from thousands of feet away. Over a dozen people were on the reactor's roof or working nearby when the roof structures collapsed due to the explosion. Three workers fell into the thick slurry; one was rescued with great difficulty, while two died. The explosion threw nearby workers, including the welder, and two of them died instantly.
UK, 2020	Explosion	An explosion occurred inside an AD silo during some maintenance hot works, leading to 4 deaths. The silo was producing biosolids and had been producing methane simultaneously, which had been ignited, leading to the explosion.
UK, 2023	Fire, Explosion	Due to unregulated and unsafe electrical protection, an unexpected lightning strike at a recycling plant ignited the biogas in the gas collection domes above the tanks, leading to an explosion. No injuries were reported.