Polymers case study

Part C: Gas fermentation

1 Introduction

Gas fermentation is a biotechnological process that utilizes gaseous feedstocks such as carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2) and oxygen (O_2) for microbial fermentation at industrial scale to produce chemicals and fuels. The ability to process gaseous feedstocks distinguishes it from traditional fermentation processes that rely on sugars or oil as a feedstock. It leverages the metabolic capabilities of specialized microorganisms, such as acetogens and methanogens, to convert waste gases into valuable chemicals and fuels.

At the core of gas fermentation is the use of anaerobic microbes that possess the Wood–Ljungdahl pathway, a biochemical route enabling the fixation of CO_2 and CO into acetyl-CoA, a key metabolic intermediate co-enzym that plays a vital role in living cells in the Krebs cycle. From the acetyl-CoA intermediate, a wide range of products, including ethanol, acetate, butanol, and more complex molecules like bioplastics such as bio-PET, polylactic acid (PLA) and polyhydroxyalkanoate (PHA) or jet fuels or even proteins can be produced via biosynthesis. The process is typically carried out in bioreactors in aqueous media at low temperature and depends on multiple variables that influence the efficiency of the microorganisms, such as gas composition, pH, temperature, nutrients,…

Industrially, gas fermentation has gained traction due to its potential to valorize industrial off-gases from steel mills, refineries, and chemical plants. Companies like LanzaTech have pioneered commercial-scale applications, demonstrating the feasibility of converting waste gases into marketable biofuels and chemicals. Gas fermentation represents a promising frontier in industrial biotechnology, offering a circular and low-carbon pathway to produce essential commodities. As advancements in microbial engineering and reactor design continue, gas fermentation is poised to play a pivotal role in the transition toward a more sustainable bioeconomy. While gas fermentation can produce a broad range of products, in this report the focus will be put primarily on applications in the materials sphere (either through the production of key industrial monomers, or the direct production of polymers).

2 Technology description

2.1 Overview

Gaseous carbon sources are used as the main feedstock for gas fermentation processes, where also H_2 can be added as an additional energy source in the process. The gas fermentation process takes place through the digestion of the gases by micro-organisms. The most well-known process uses acetogenic bacteria in the Wood-Ljungdahl pathway or acetyl-CoA pathway. These bacteria can produce several alcohols through anaerobic fermentation. Commercial applications use mainly *Clostridium ljungdahlii* and *C. autoethanogenum* strains.[1,2] In this pathway, the bacteria are able to ferment CO, and can therefore directly use syngas or other CO rich sources such as blast furnace emissions from steel industry as a feedstock source. The overall reaction pathway in the case of ethanol as product can be summarized as:

$$6CO + 3H_2O \rightarrow C_2H_5OH + 4CO_2$$

When targeting a gas fermentation process to produce alcohol from captured CO_2 emissions, the usage of 3 molar equivalents of H_2 gas is required as an (expensive) additional feedstock. The overall chemical conversion of CO_2 in the Wood-Ljungdahl pathway can be summarized as:

$$2CO_2 + 6H_2 \rightarrow C_2H_5OH + 3H_2O$$

Aerobic bacteria can be used for gas fermentation using the Calvin-Benson-Bassham (CBB) cycle. This metabolism allows high biomass production and the synthesis of more complex products, including polyhydroxyalkanoates (PHA).

The overall gas fermentation process can be divided into four steps:

1. Accumulation or generation of (syn)gas
2. Gas pretreatment
3. Gas fermentation in a bioreactor
4. Product separation

In the gas fermentation step, the gas is added in a bioreactor with appropriate microorganisms in an aqueous medium under optimized conditions. Next to the type of microorganisms, the yield and purity of the targeted products can also depend on the bioreactor design, gas composition and supply rate, temperature, pH, agitation, nutrients, etc. A high solubility of the gaseous substrates in the medium is required to make sure there is a good substrate availability during the reaction, and gas pressurization is usually required to achieve this[3]. At smaller scale, continuous stirred tank reactors are most used, for moving to industrial scale, reactor types like bubble columns, loop and immobilized cell columns are preferred to lower the stirring energy demand.

Product separation after the fermentation step can be done by appropriate separation and purification techniques, depending on the targeted product. More complex products can require a coupled process with several fermentation steps such as an acetate fermentation to lipids (TAGs) fermentation or a fermentation step coupled to a catalytic process such as an ethanol fermentation coupled to alcohol-to-jet catalytic process to produce jet fuels.

[1] Liew et al. *Front. Microbiol.* **2016**, 7 DOI: 10.3389/fmicb.2016.00694
[2] Burk et al. *Trends in Biotechnology*, **2016**, 34, 3, 187-190 DOI: 10.1016/j.tibtech.2015.10.007
[3] Van Hecke et al. (2019). *Bioresource Technology*, *293*, 122129. https://doi.org/10.1016/j.biortech.2019.122129

To build up the PHA polymers, the bacteria need to be fed with the right feedstock sources, being mainly CO, CO_2, O_2 and H_2. The Calvin cycle requires ~8 molar equivalents per mole of CO_2, resulting in a strong dependence on the availability of (green) H_2 to produce PHA in a sustainable manner[4].

2.2 CO_2 input specifications

The feedstock gases can have various origins. In general, gas fermentation is quite tolerant for different impurities in the feed gas. For example, in one investigation it was shown that, as compared to using pure CO_2, the use of real off gases did not affect bacterial performance nor the properties of the biopolymers produced in the process [5]. Similarly, Lanzatech has indicated that the gas fermentation technology is tolerant to many impurities, avoiding the complex steps required to purify the exhaust gas[6]. Sulfuric components, which often poison metal-based catalyst, can be tolerated. However, some specific impurities such as particulates, tars, aromatics or NOx do require removal[1].

3 Market aspects

3.1 Market volumes & trends

Gas fermentation processes can produce a wide array of platform chemicals, such as acetate, and alcohols, for example ethanol or butanol, and can therefore feed into all end-applications that use these chemicals in their production processes. Also the bio-fuel market can be targeted through production of bio-ethanol, a market that was valued at USD 72.5 billion in 2024 and is estimated to reach USD 206.1 billion by 2034 as ethanol biofuel is increasingly becoming a cleaner road transport option to gasoline.[7] Gas fermentation is however not the main production technique of bio-ethanol, which is most commonly produced from corn or sugarcane, by major industrial players such as Cargill, Chevron, Neste, TotalEnergies and UPM.

Gas fermentation processes can also be used in the production processes of several plastics such as PET, PLA, PBS or PHA via microbial fermentation. PET is produced from monoethylene glycol (MEG) and terepthalic acid, where MEG can be produced through a gas fermentation process, resulting in PET with around 30% of renewable content. PET is used in a broad range of applications such as packaging products and textiles and represented a USD 42 billlion market in 2023, expected to grow to USD 63 billion by 2032.[8] PLA is an industrially compostable plastic that is produced through a polymerisation of lactic acid that can be produced via microbial fermentation of gaseous feedstock, although it is most commonly produced through fermentation of plant starch such as from corn, cassava, sugarcane or sugar beet pulp. PLA has important applications in packaging and consumer goods such as cutlery, but also in agricultural and medical applications. PLA material is often used in additive manufacturing processes. The global PLA market size was USD 1.25 billion in 2023 and is projected to grow to USD 4.2 billion by 2032.[9] Polybutylene Succinate (PBS) is a biodegradable aliphatic polyester that is produced through the polymerisation of succinic acid and butanediol that can be formed through gas fermentation techniques. Currently, PBS is mostly derived from petrochemical feedstock, but operations from biobased feedstock are also commercially produced in the market by PTT MCC, a JV between Mitsubishi Chemical Corporation and PTT Global Chemical Public Company. The markets of

[4] Vlaeminck et al. (2022). *Journal of Biotechnology*, *343*, 102-109. https://doi.org/10.1016/j.jbiotec.2021.11.010
[5] Garcia-Gonzalez & De Wever (2017). *FEMS Microbiology Letters*, *364*(20), fnx196. https://doi.org/10.1093/femsle/fnx196
[6] LanzaTech and BASF achieve first milestone in utilizing industrial off-gases for chemical production
[7] GMI - Ethanol Biofuel Market Size, 2025-2034 Trends Report
[8] Data Intelo - PETE Market Report | Global Forecast From 2025 To 2033
[9] Fortune business insights - Polylactic Acid Market Size, Global Forecast, Report, 2032

PBS products are related to packaging, textiles and automotive applications.[10] The global PBS market was valued at USD 115 million in 2023 and is expected to expand at a compound annual growth rate (CAGR) of 12.2% from 2024 to 2032.[11]

In contrast to earlier mentioned plastics for which precursors are produced through fermentation, PHA polymers are directly produced in nature by microorganisms. A culture of micro-organisms in a suitable medium can produce predictable PHA polymers when fed appropriate nutrients. While the direct production of PHA through gas fermentation has been demonstrated at lab scale from industrial waste gas streams containing CO_2[12], PHA is currently typically produced through the fermentation of sugar or vegetable oils. The PHA polymer family can produce PHA plastics with a very broad range of properties making it potentially suitable for a broad range of applications similar to those of the commodity plastic polypropylene. PHAs have currently achieved some degree of market penetration in packaging, food service, agriculture and medical products.[13] The current market size of PHA was valued at USD 123.5 million in 2024[14] and remains low in comparison with the polypropylene market. Further R&D work to improve i.e., the processability and stability will facilitate its market uptake for applications in sectors.

3.2 Commercial projects and pioneers

Industrial gas fermentation has been demonstrated in the market through commercial processes that go beyond the pilot phase. Pioneering companies such as Calysta, Unibio and LanzaTech operate commercial installations based on different setups. Calysta generates 20 kton of protein annually for aquaculture with plans to expand their capacity towards 100 ktons/y[15], using methane as feedstock[16]. Unibio operates a gas fermentation process that converts methane into biomass for fishmeal with a capacity of 6 kton/y.

LanzaTech started up their first gas fermentation plant in 2018, producing 46 kton of ethanol per year from steel mill emissions and are currently operating 6 commercial plants, the largest one located in China with an annual capacity of 60 kton ethanol from steel industry emissions.[17] LanzaTech's chemical building blocks have been used in several end-applications such as running shoes, textiles and as Sustainable Aviation Fuel (SAF). Arcelor Mittal's Steelanol plant in Ghent, Belgium uses its technology to produce ethanol from captured blast furnace emissions of the steel industry with a current production capacity of 1000 tons per year, in the long-term aiming towards the capacity to produce 80 million litres per year of ethanol.[18] The market viability of the Steelanol is in part driven by the recognition of the produced ethanol as a recycled carbon fuel (RCF), and avoiding the purchasing cost of emission rights in the Emission Trading System (ETS). However, the process is struggling to meet the strict EU regulatory requirements of the Renewable Energy Directive (REDIII), and the ETS tax remains due, undermining the business case of the process.[19]

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[10] Grand view research - https://www.grandviewresearch.com/industry-analysis/polybutylene-succinate-market-report

[11] GMI - Polybutylene Succinate Market Size, Share & Global Report - 2032

[12] De Wever, H., Garcia-Gonzalez, L. *Microbial Processes: Production of Polyhydroxyalkanoates from CO2. In: Kircher, M., Schwarz, T. (eds) CO2 and CO as Feedstock*. **2023** DOI: 10.1007/978-3-031-27811-2_10

[13] GO!PHA

[14] GMI - Polyhydroxyalkanoate Market Size, Share & Analysis Report, 2034

[15] First industrial-scale FeedKind® facility heralds new era of food security – Calysta

[16] Can gas fermentation deliver on its promise for food and feed?

[17] Lanzatech - Lanzatech A Carbon Recycling Company Corporate Presentation 2023

[18] Steelanol - Steelanol - Fueling a sustainable future

[19] Steelanol - De Tijd

Jupeng Bio operates a biofermentation process that converts syngas into bioethanol in a time scale of a few minutes at low temperatures and pressure with a high tolerance to variations in syngas composition and impurities.[20] Mango materials is scaling up and commercializing a biomanufacturing technology to produce PHA from methane gas in the US, leveraging biogas from a wastewater treatment plant.[21] The biotech company Again captures CO_2 from point emissions and converts them to industry standard drop-in chemicals without the need for pre-treatment and with a high impurity tolerance, albeit currently still using grey hydrogen as feedstock.[22] Again is active in 3 facilities of which 2 in the EU (Denmark & Norway) and one in Texas, USA. Airprotein uses gas fermentation processes to produce protein for food applications from captured CO_2. [23]

In conclusion, gas fermentations are already industrially applied for a number of applications, however often starting from an energy rich (waste) gas such as CO and CH_4, and not CO_2 which would require the corresponding production of large amounts of green H_2, which is still very expensive today (see case studies on e-fuels).

4 Economics

Gas fermentations processes have a number of distinct features as compared to thermocatalytical or electrocatalytical CCU routes. An overview of key strengths and weaknesses is displayed in Figure 1. Undoubtedly one of the main strengths is the catalytical power, i.e., the ability to synthesize complex molecules with high selectivity in (often) just a single process step, where other technologies would need a series of steps to achieve the same result. Another strength is that processes can be operated at mild conditions, although usually some level of pressurization of the gases is required to increase solubility in the aqueous medium where microorganisms are present. Furthermore, as discussed above, pure CO_2 is not required, saving on purification costs.

Among the challenges often encountered are the lower productivity rates and the low concentrations of products in the reaction mixture. The latter can be a problem especially when the target product is a liquid. Taking ethanol as an example, for a typical outlet concentration of 6 wt%[24], the corresponding energy requirement to purify the product (i.e., remove all the water via distillation) is about 20% of the energy content of the molecule[25]. Also, in case of PHA production, the downstream processing is known to be an important cost factor[26].

[20] Jupeng Bio - Fermentation Technology - JupengBio
[21] Mango materials - Gas Fermentation to Enable Decentralized Local Biomaterials Manufacturing — BioMADE
[22] Again - Again Bio's bacteria eats exhaust and spits vinegar | TechCrunch
[23] Airprotein - Air Protein | About Air Protein
[24] Garcia-Gonzalez, et al. *Onderzoek naar mogelijk ondersteuningsbeleid mbt nieuwe toepassingsmogelijkheden van CO2 als grondstof/feedstock*. Vito, 2016.
[25] Huang & Zhang. Energy & Environmental Science 4.3 (2011): 784-792.
[26] Shinde et al. 2025 *Trends in Biotechnology* Volume 43, Issue 5, p. 1140-1165

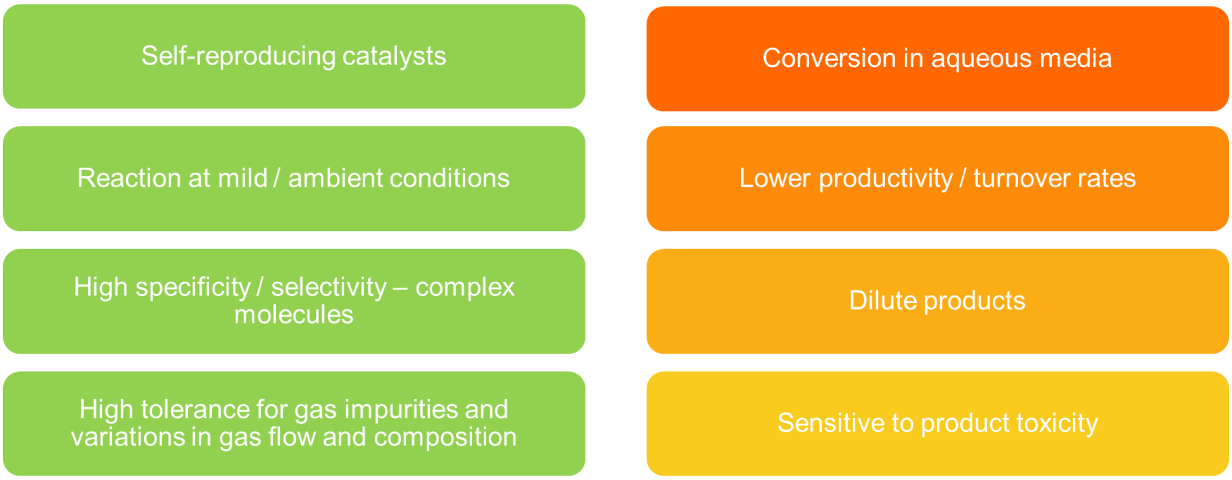

Figure 1 Overview of strengths and weaknesses of gas fermentations (source: VITO)

In case of PHA, a key aspect for future research is to identify the most optimal fermentation route. More concretely, two routes can be distinguished: (i) gas fermentation of CO_2/H_2 directly into PHA (ii) converting CO_2/H_2 into a liquid feedstock such as acetic acid, which subsequently can be converted into PHA. Evidently, the latter option holds more process steps (two fermentations instead of one, in the case of acetic acid as intermediate) which is not advantageous, however, the hydrogen efficiency is much better in the indirect route[27,28]. Considering the elevated cost of green hydrogen today[29], this aspect may be a decisive factor in cost comparisons.

[27] Vlaeminck, E., et al. *Journal of Biotechnology*, 2022, 343: 102-109.
[28] Garcia-Gonzalez, L., & De Wever, H. (2018). *Applied Sciences*, *8*(9), 1416.
[29] Eblé, L. F. J., & Weeda, M. (2024). Evaluation of the levelised cost of hydrogen based on proposed electrolyser projects in The Netherlands: Renewable Hydrogen Cost Element Evaluation Tool (RHyCEET). *Repository. Tno. Nl*.

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