Bio-based solutions for carbon capture

In classical applications of CO2 capture, the motivation has not been greenhouse gas emissions reduction. The technologies used have also been based on conventional adsorption and stripping towers with solvents such as amines, glycols, and hot potassium carbonate. But the world of carbon capture is changing. The motivation is expanding beyond hard economics and process efficiency to include greenhouse gas emissions reduction to mitigate climate change. Furthermore, the breadth of available carbon capture technologies is widening to include bio-based solutions.

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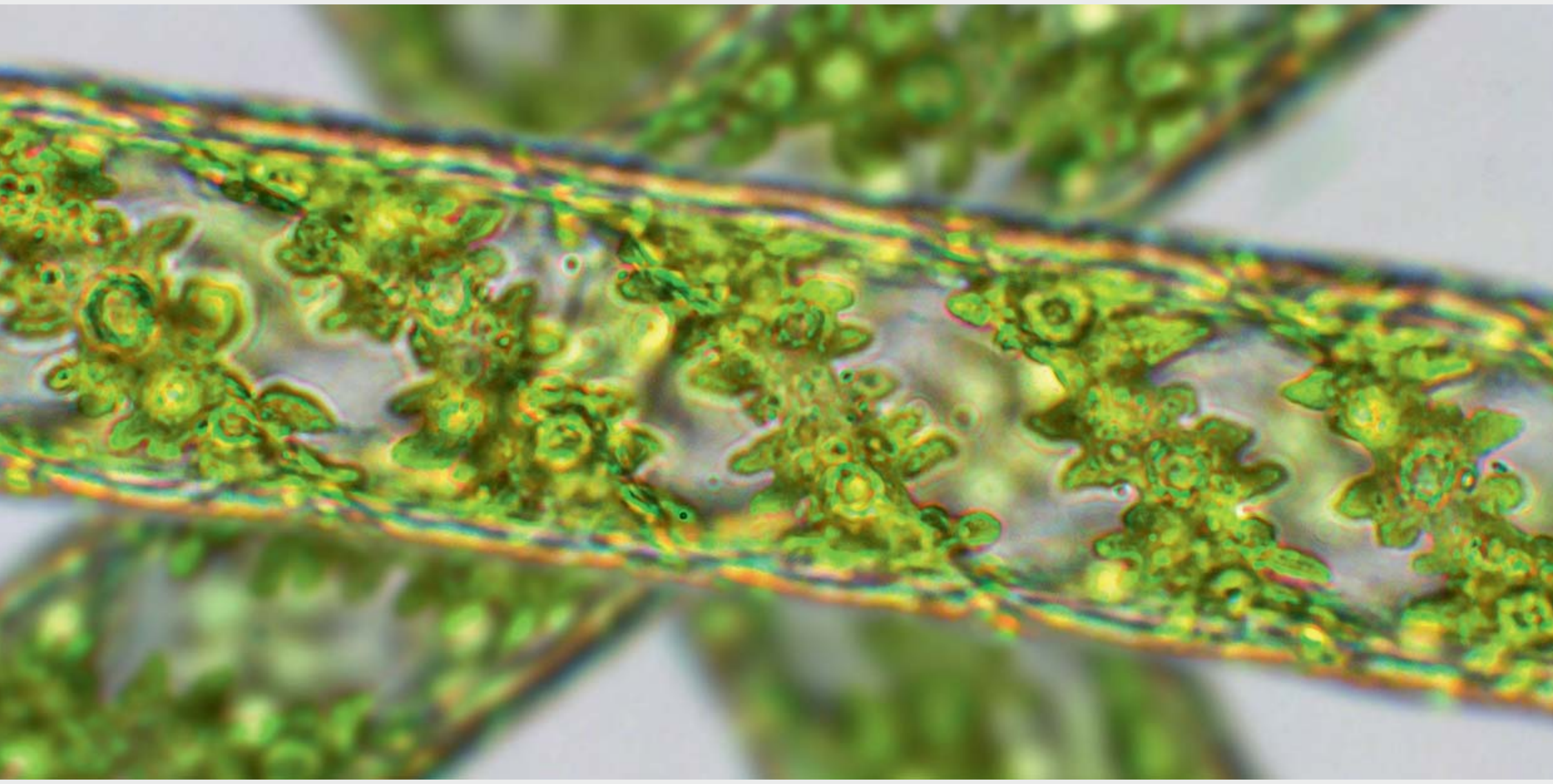
Learning from nature has served mankind well for decades. Alexander Flemming's discovery of penicillin led to the development of modern antibiotics which have transformed modern healthcare. Biotechnology is now an instrumental technology for producing a wide range of medicines.

Biotechnology, algae, and bio-based solutions can also be applied to yield energy efficient methods of carbon capture. Beyond that, bugs can convert carbon to chemical intermediates such as acetic acid and ethanol. Ethanol can also be processed through dehydrogenation and oligomerisation to yield synthetic aviation fuel (SAF). Ethanol is also a fuel in its own right and is blended with gasoline at up to 15% in the USA and 10% in Europe.

Enzymatic enhancement of HPC CO_2 capture

Hot potassium carbonate (HPC) has been used for decades as a solvent for CO_2 capture. The process was developed in the 1950s and was modified by two engineers: Benson and Field. In honour of their contribution, it subsequently became known as the Benfield Process. It is now licensed by Honeywell UOP.



However, many innovations have taken place since Benson and Field were involved. As an example, the UOP Benfield ACT-1 activator can be added to the potassium carbonate solvent to improve the CO_2 absorption rate and increase the CO_2 loading. It can reduce the solvent recirculation rate and thereby results in less energy being required to heat and regenerate the solvent in the stripping column. ACT-1 is a proprietary organic additive which is incorporated into the hot potassium bicarbonate solution at between 1 and 3%.

Biotechnology has recently been exploited to catalyse CO_2 absorption in the HPC process using Carbonic Anhydrase (CA). CA is an enzyme which plays an essential role in humans and other species. Its function is to remove CO_2 from blood. In humans, CO_2 is produced naturally through respiration. Respiration is the breaking down of molecules in combination with oxygen to release energy in the body. The chemistry and function or respiration is similar to the combustion of hydrocarbons.

CO_2, which is released into blood through respiration, must be broken down to avoid strong pH changes. The CA enzyme supports that by catalysing the reaction of CO_2 with water to form bicarbonate and hydrogen ions: $CO_2 + H_2O \rightarrow HCO_3^- + H^+$. Subsequent reactions convert these ions to harmless products in the blood.

A proprietary CA enzyme known as 1T1 is now being used by *CO_2 Solutions by Saipem* on industrial CO_2 capture systems. The molecular structure of the 1T1 enzyme has been engineered to maximise its catalytic efficacy to promote the absorption of CO_2 into the hot potassium carbonate solution whilst also allowing low-cost manufacture of the enzyme.

Novozymes, part of the Danish biotechnology giant Novo Nordisk has entered into an agreement with Saipem to manufacture the 1T1 CA enzyme on an industrial scale to enable the commercialisation of Saipem's bio-based *CO_2 Solutions* carbon capture technology.

Biomanufacturing using captured CO_2

Trees and plants absorb CO_2 as they photosynthesise. They use the carbon to create carbohydrates, starches, and lignin that are required to build their leaves and branches.

Bacteria can also consume CO_2 to produce valuable chemicals such as acetic acid in a process known as gas-fermentation. This is an established technology where gases such as CO_2, CO, H_2 or CH_4 are fed into a bioreactor which contains a microorganism that can metabolise these gases and convert them to higher hydrocarbons.

The Danish startup Again has developed a gas fermentation process that utilises captured CO_2 as a feedstock to enable competitive industrial production of green chemicals. By combining millennia-old bacteria with modern biotechnology, Again's novel biomanufacturing process can convert CO_2 into carbon-neutral or carbon-negative chemicals.

A convenient aspect of the Again process is that flue gases from industrial emitters can be fed directly into their bioreactor. No pre-purification is needed since the bacteria can deal with the most typical flue gas impurities such as NOx, SOx, and dust.

The lineage of the bacterium that Again uses evolved naturally hundreds of millions of years ago when the level of atmospheric CO_2 was much higher than today. The result is that their micro-organism naturally wants to consume CO_2.

Hydrogen is mixed with the flue gases in Again's bioreactor. This hydrogen is the main energy input to the process. Within the bioreactor, bacteria fix the CO_2 and the hydrogen and produce dilute aqueous chemical products. These products are withdrawn from the bioreactor and purified to be ready for offtake.

When used to produce acetic acid, 1.6 tonnes of CO_2 are captured by the Again process to make each tonne of acid. 0.6 tonnes of CO_2 are released through the process meaning that 1 tonne of CO_2 is utilised.

The classical method of acetic acid production from fossil fuels would typically emit 2 tonnes of CO_2 to produce an equivalent amount of acid. When combining green hydrogen with the captured CO_2, the overall life cycle analysis of the Again process results in 3 tonnes of CO_2 emissions reduction per tonne of acetic acid produced.

The bacterium is thermophilic and requires no light for growth. The process is therefore extremely compact. These are advantages of over the use of algae for CO_2 capture. A single Again bioreactor with a diameter of 4 m, can fix around 10,000 tonnes of CO_2 per year. The company has constructed a demonstration facility close to Copenhagen that is currently producing and selling commercial grade acetate.

Gas fermentation of ethanol

The US-based company LanzaTech utilises an anaerobic acetobacter bacterium in a gas fermentation reaction to convert CO-rich feed gases

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to ethanol and a range of biochemicals. Subsequently, the complimentary LanzaJet process can be used to convert the bioethanol to synthetic aviation fuel (SAF) in their proprietary 'Ethanol to Jet' or ETJ process.

CO_2-rich streams can potentially be utilised by the LanzaTech process, in combination with hydrogen. But a high CO content in the feed to the bioreactor, or fermenter, reduces the green hydrogen feed requirement. Syngas derived from waste or biomass gasification is generally CO-rich and is a good feedstock for the LanzaTech process.

Iron and steel making also yield CO-rich flue gases which are ideal feedstocks to the LanzaTech process. Blast furnace gas (BFG) contains 20% CO and converter gas (also known as basic oxygen furnace gas or BOFG) contains 60% CO. At present, the energy rich converter gas, typically with a lower heating value (LHV) of 3 kWh/Nm^3, is often utilised on the iron and steel making facility for heat or power generation on a gas engine. Alternatively, it is flared.

Blast furnace gas has a lower energy value due to the lean CO concentration and higher CO_2 content (LHV 0.9 kWh/Nm^3). It can also be utilised on the facility or is sent to the flare. Utilisation of BFG in the LanzaTech process can generate valuable bioethanol.

LanzaTech's process was demonstrated at pilot-scale in 2008 using flue gases from the BlueScope Steel mill in Glenbrook, New Zealand. Since then, LanzaTech has deployed its technology at two 300 tonne per annum demonstration facilities at Baosteel Shanghai and Shougang Steel Caofeidian in China.

These initial deployments of these LanzaTech fermenters are fed with a range of iron and steel making off gases including BOFG, BFG, and coke oven gas (COG). In a future project called 'Dragon', which is part of the UK's 'Jet-Zero' ambitions, Tata Steel at Port Talbot in South Wales will deploy the LanzaTech and LanzaJet processes to create ethanol and convert it to aviation fuel.

CCS from seawater

The British startup Brilliant Planet has developed a CO_2 capture process that relies on algae. The Brilliant Planet concept is ideally located next to nutrient-rich seawater in a desert location and their demonstration plant in Morocco is a good example of that.

Seawater containing natural bicarbonate ions is pumped into a lagoon filled with algae. Nutrients in the seawater are absorbed by the algae. The algae simultaneously absorb CO_2 from ambient air above the lagoon in a form of direct air capture of CO_2.

CO_2 is also captured via a second mechanism. The algae consume bicarbonate ions from the seawater as they grow and multiply. The bicarbonate ions have previously been created naturally during absorption of atmospheric CO_2 by the seawater.

The algae that have grown in the lagoon are harvested and dried using natural sunlight and spray drying in the warm, dry desert air. The dried biomass is then buried under sand in the desert. At this stage, the algae is dry, salty and acidic. For each of these three reasons, it cannot biodegrade in the desert sands to release methane or CO_2 as greenhouse gas emissions. This ensures that the captured CO_2 is sequestered for 1,000 years, or more.

The lagoon water with a reduced bicarbonate content is released back into the sea where it re-absorbs CO_2 from the atmosphere. This is also a natural form of direct air capture of CO_2 which also contributes to the reduction of atmospheric CO_2 through the Brilliant Planet process.

The origins of carbon capture

CO_2 capture has its origins in enhanced oil recovery (EOR), sour gas processing and CO_2 removal from syngas during ammonia production. In ammonia production, CO_2 must be removed to maximise the yield of the ammonia synthesis loop through protecting the catalyst. When urea is the target product, that captured CO_2 can be combined with the ammonia to yield urea. Sour gas contains CO_2 which can be removed to increase the calorific value of the natural gas and minimise the energy requirements for natural gas compression and pipeline transmission.

Captured CO_2 can be used to extend the life of depleted oil fields when utilised for EOR. The Petra Nova coal fired power plant, operated by NRG Energy in Texas, captures CO_2 for this purpose. It uses an amine-based solvent from Mitsubishi Heavy Industries in a twin-tower absorber and stripper system to capture post-combustion CO_2 from the low-pressure flue gas.

Additional heat must be generated by the power plant to boil CO_2 from the amine solvent in the stripper, thus CO_2 capture comes at an additional cost. CO_2 capture at Petra Nova is economically viable when oil prices are high, but it becomes unprofitable when oil prices fall. Petra Nova ceased CO_2 capture in 2020 when crude prices hit a low due to Covid but recently restarted as the price of West Texas crude broke through USD90 per barrel.