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What can chemical engineers do to mitigate climate change?

Chemical engineers are people who design, develop and manage a wide spectrum of industrial processes. (1) This places them in a unique and invaluable position when it comes to climate change, one of the defining issues of our time. They are able to instigate change across the industrial sectors to combat the causes of climate change through reducing anthropogenic greenhouse emissions, particularly from carbon dioxide (CO_2). This is done through designing better processes and developing carbon capture and storage technologies. (2)

This essay is going to explore a number of remarkable developments that are being made by chemical engineers to innovatively tackle the issue of climate change. These include:

- Removing CO_2 using nitrogen doped biochar beads as a green absorbent
- Selecting the greenest synthesis
- Improving industrial processes to reduce CO_2 emissions
- Alternative methods of ammonia production
- Reducing CO_2 emissions from food production
- Turning captured carbon into useful products

Removing CO_2 using nitrogen doped biochar beads as a green absorbent

Carbon capture is a process chemical engineers are heavily involved in and the methods they use are constantly evolving. Biochar is an extremely promising CO_2 absorbent since as well as being highly porous, it is also of low cost, widely available and renewable. It is a solid carbon material produced by the pyrolysis of biomass and when nitrogen doped its absorbency is enhanced considerably. (3)

Biochar is nearly 10 times lower in cost than other CO_2 absorbents due to the environmentally friendly and affordable source of biomass materials, carbon based biological material derived from living or recently living organisms. These are readily available and include bamboo, fungi and potato starch. This means biochar is a sustainable material since it is prepared from renewable biomass making it a great hope for the future as it will always be an available option. Furthermore, biochar is prepared by the attractive process of pyrolysis, thermochemical decomposition in an oxygen deficient environment, using simple and inexpensive technology. (3)

The CO_2 absorption of biochar depends on both physical and chemical properties. These include: its porosity, basicity (ability to accept a proton to form a stable product), surface functional groups, presence of alkali and alkali earth metals, polarity and aromaticity. Chemical engineers have the ability to optimise its CO_2 absorption by using different routes of preparation, both chemical and physical modification and impregnation with elements. One particular success has been nitrogen doping, with doping meaning the addition of an impurity, in this case nitrogen, to achieve a desired characteristic. N-doping has been shown to considerably enhance the absorption of biochar, this is because N-rich functional groups enhance surface affinity between basic sites and CO_2. (3)

Ammonia, amine groups (primary, secondary and tertiary) and polymer based amines are used to introduce nitrogen to biochar. Ammonia is widely used and urea is also common as it is a cheap and non-toxic amine group. The amine groups strongly and selectively bind CO_2 via chemisorptive interactions with CO_2 molecules forming a carbamate. (3) The key stages of this process of developing biochar for CO_2 absorption are outlined in Figure 1 below.

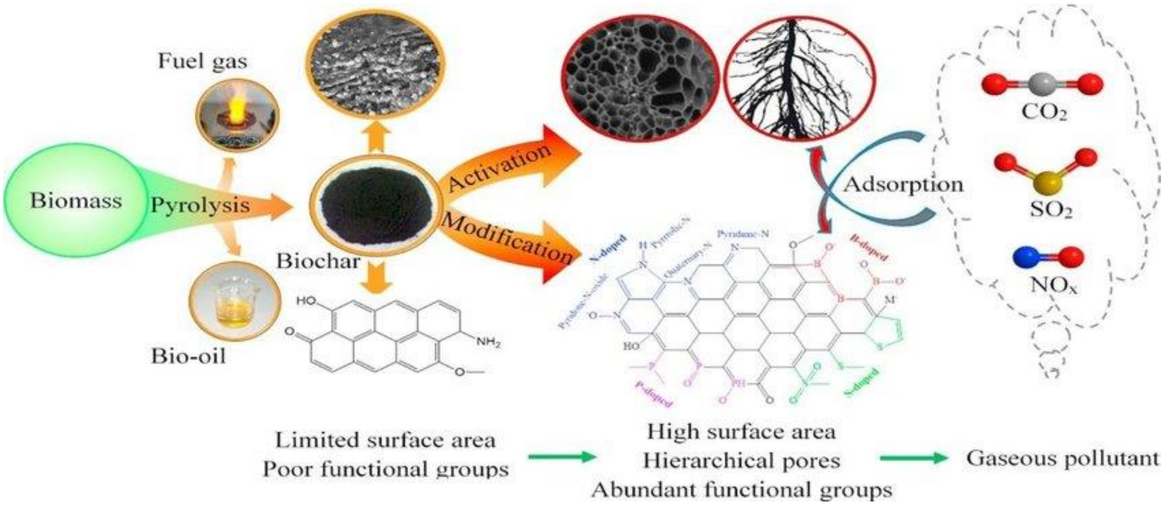

Figure 1 A diagram to demonstrate how biochar begins as biomass before undergoing pyrolysis to form the biochar which can then be modified e.g.N-doped to become better at absorbing gaseous pollutants such as carbon dioxide (4)

Chemical engineers clearly see great potential in biochar as a CO_2 absorbent since the University of Nottingham is leading a £4.5million study into the viability of biochar to store CO_2. Professor Colin Snape (Director of the Nottingham's EPSRC Centre of Doctoral Training in Carbon capture and Storage and Cleaner Fossil Energy) stated that "The aim is to take carbon from atmospheric emissions and trap it in the biochar. That carbon will then be locked in the soil for centuries, if not millennia, so its sustainable production could be a powerful tool in the fight against climate change. However, we need to get a detailed and accurate picture of the longevity and stability of biochar carbon in soils to ensure it has no detrimental impact." (5) This study will give valuable insights into the efficacy of biochar and enable chemical engineers to determine if it is a worthwhile technological solution to help mitigate climate change.

Selecting the greenest synthesis

Chemical engineers are always looking to use the greenest methods of synthesis in industry. They can use measures such as Life Cycle Assessments (LCAs) and atom economy to help them determine which methods will have the least environmental impact. (6) There can often be many different processes to synthesise the same end product but some are far more detrimental to the environment than others, so it is vital to carefully choose the greenest method with the aim to avoid unnecessary damage.

An example of more environmentally friendly synthesis that has been developed is a new method for the production of ethyl acetate from alcohol without using acetic acid. This involves atmospheric CO_2 being converted into starch by photosynthesis, harvested and fermented into ethanol which is chemically converted to ethyl acetate. (1) This is a better method, especially since it uses up CO_2. Another example of a greener method of synthesis is CO_2-free production of methanol, an important feedstock for the chemical industry. In the new process, syngas is produced by partial oxidation of natural gas or biogas, rather than steam or autothermal reforming. This produces no CO_2 emissions and the other steps of methanol synthesis and distillation remain basically the same with a few adaptations to deal with waste gas streams effectively. (7) This is a great breakthrough due to the widespread use of methanol in industry.

Ultimately, chemical engineers will try to use the method of synthesis that produces the least CO_2 in order to help restrict climate change. However, they will not just consider the final reaction in the manufacture of a product. They will look at the whole life cycle considering the CO_2 released at each stage of its production.

Improvements to industrial processes to reduce CO_2 emissions

In industry, it is useful to revaluate processes to see if there are any improvements that can be made to make it more efficient and hence reduce CO_2 emissions. They can analyse a process in detail and assess which aspects are the least efficient and then come up with technological solutions to the problems.

In BP refineries it was discovered that fired heater tubes can be fouled with certain crude oil components which reduce heat transfer efficiency, increasing pressure drop and shortening run times. To improve efficiency they decided to install specially designed springs which increased heat transfer by 50% and reduced fouling by 70% doubling the run length. The springs cleaned the tube by fluid passing through the tube making the springs vibrate and continuously scrape the insides of the tubes. On-line cleaning with combustible abrasives also removes scale without having to shut down the line. Due to this, one refinery experienced a drop of 1,800 tonnes of CO_2 emissions per year. (8) This signals significant progress and demonstrates the positive impact chemical engineers can have in reducing CO_2 emissions in industry. Even just small adjustments to processes can have huge benefits.

A major project that hopes to improve industrial processes is the SynHiSel project currently running at UK universities, including Bath. It aims to develop new, more efficient chemical processing technology with the anticipation of saving hundreds of millions of tonnes of CO_2 emissions. It will focus especially on improving the selectivity of separating membranes. This is a huge project and has received £9 million of funding indicating the importance placed on improving industrial processes. (9)

Alternative methods of ammonia production

Industrial ammonia production, using the Haber-Bosch process, emits more CO_2 than any other chemical making reaction, more than half of these coming from the hydrogen production. Some green ammonia plants are being developed using renewable energy and feedstocks to generate hydrogen instead of fossil fuels.

An alternative to the Haber process is the electrochemical reduction of nitrogen over a catalyst, which has inspired the imagination of many chemical engineers. A voltage is applied across an electrochemical cell to drive water oxidation and nitrogen reduction simultaneously. (10) The catalyst at the anode oxidises water to hydrogen ions which are electrochemically transferred to the cathode and a different catalyst at the cathode reduces nitrogen to ammonia, as demonstrated by Figure 2 below. (11)

Equations for the electrochemical reduction of nitrogen -

Anode: $3H_2O \rightarrow {}^3/_2\, O_2 + 6H^+ + 6e^-$

Cathode: $N_2 + 6H^+ + 6e^- \rightarrow 2NH_3$

Overall equation: $N_2 + 3H_2O \rightleftharpoons 2NH_3 + {}^3/_2\, O_2$

(11)

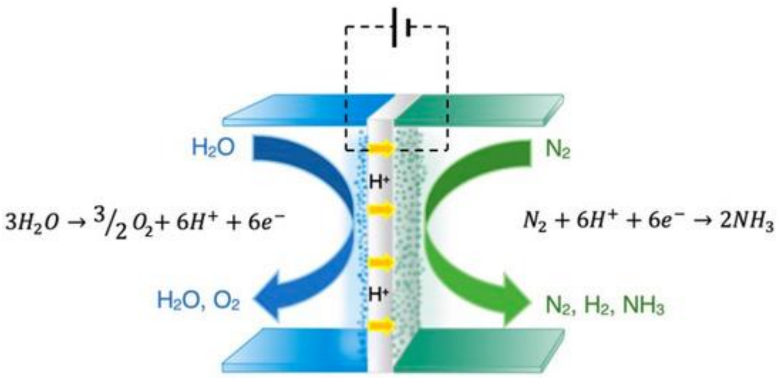

Figure 2 Diagram to demonstrate process inside of an electrochemical cell (11)

There are different options for catalysts including noble-metal nanostructures, metal oxides, metal nitrides, metal sulphides, nitrogen and boron doped carbon and lithium. (11) The purpose of the catalyst is to overcome the high energy required to break the strong nitrogen triple bond indicated by the large bond enthalpy of approximately 1000 $kJmol^{-1}$. When these systems were first developed in 2019, they produced 40% ammonia and 60% hydrogen but the goal is 99% ammonia. (10) Development of electrochemical synthesis of ammonia is moving ahead with improvements and progress is being made to bring this process into industrial practice. (11)

Another process that has demonstrated some potential involves lithium nitride. Lithium reacts readily with nitrogen in the air producing lithium nitride which reacts violently with water to produce ammonia and lithium hydroxide. (12) Chemical engineers are also researching other methods of green ammonia production. This is extremely positive in terms of mitigating climate change since it means ammonia production will no longer need to involve the emission of vast amounts of CO_2 as there will be so many other options available. Since ammonia is commonly used, particularly in fertilisers, this means the negative impact of industries using ammonia, such as food production, is significantly reduced.

Reducing CO_2 emissions from food production

Food accounts for 26% of greenhouse gas emissions (13) meaning food production plays a crucial role in the climate change story. Chemical engineers are constantly looking for ways to reduce the impact of food production by designing new processes and improving existing ones.

One fascinating example that chemical engineers have developed is the use of microbes to produce proteins for animal feed, for example for fish as outlined in Figure 3 below. The microbes consume CO_2 and reproduce allowing single celled protein to be harvested. This will be hugely beneficial in reducing emissions from the agricultural sector as not only is CO_2 used to make the protein but using the protein for animal feed as opposed to soy also cuts the emissions that would have been involved in the production of soy. (14) There is so much scope for chemical engineers to make improvements in food production and they continue to explore new ideas to help reduce CO_2 emissions.

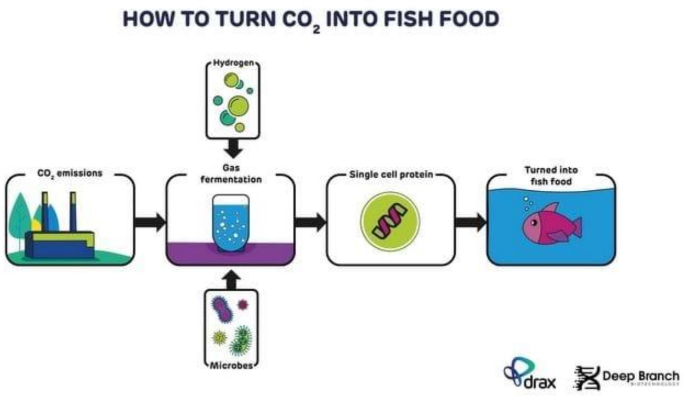

Figure 3 A flow chart to demonstrate the stages of turning CO_2 into fish food (14)

Turning captured carbon into useful products

Carbon capture and storage (CCS) is a well know technology that helps alleviate climate change but chemical engineers are seeking uses for the captured CO_2. At one level CCS is introduced to capture emissions from industrial processes but at another level the CO_2 can be used as a raw material effectively locking in the carbon and storing it for the long term. (15)

Many companies have invested heavily in finding uses for CO_2. A company called Liquid Light uses electricity and catalysts to make chemicals from CO_2, these include ethylene glycol, a key component of antifreeze and a building block of polyester bottles and fibres. BASF, a German chemical company and Novomer, a US company have also used catalysts to produce polypropylene carbonate from captured CO_2, this is a plastic that can be used for coatings, adhesives, foam and packaging. (16) Recent technology has also enabled CO_2 to be used to manufacture a metal alternative, captured CO_2 is split into oxygen and carbon in a molten carbonate bath using electrolysis. The carbon is then repurposed into carbon nanotubes which are stronger than steel and of lower density than aluminium making them incredibly useful. (15)

Chemical engineers have also been able to use a multi-enzyme reaction to make important raw materials for fine chemicals out of CO_2, the process is called electro-biocatalytic CO_2 fixation. (17) Carbon fixation is the process in which CO_2 is converted to an organic compound by a living organism. (18) The enzymes have to be embedded in a redox-active hydrogel to provide them with a continuous supply of electrons needed for the reduction of CO_2. (17). This is an extremely valuable use of CO_2 and there is hope that lots of organic products can be made.

Utilizing captured CO_2 demonstrates remarkable progress for chemical engineers in terms of mitigating against climate change. It emphasises the importance of CCS and indicates that it is still an improving technology, there are so many possibilities for using the captured CO_2 and many have not yet been developed.

Conclusion

The contribution of chemical engineers towards mitigating climate change is astounding. Their research has led to huge advances in technological solutions, providing hope for the future. Based on research findings, developing alternative methods of ammonia production appears to be one of the most significant advancements since ammonia is used so extensively in industry hence reducing

CO_2 emissions from its production will have a large scale impact. Using nitrogen doped biochar is also a fascinating new innovation that seems to hold a lot of promise, but ultimately all their solutions are of great importance and assist in mitigating climate change. Chemical engineers have come up with so many imaginative ideas as well as evaluating improving existing technologies, and they are still continuing this process, ever seeking opportunities for improvement.

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