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From greenhouse gas to green gold: Turning agricultural methane into valuable products

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Introduction and intricacies of the subject

Agriculture can be a source of GHG emissions, and a source of solutions to climate change. Methane has a high warming potential and is emitted from livestock, manure management, rice cultivation and decomposition of organic residues and thus plays an important role in agricultural emissions. But methane has to be seen beyond being an environmental problem. It can be used as a valuable source of carbon with suitable capture and conversion technologies and as a building block for the production of fuels, chemicals and bio-based products. Advanced technologies like anaerobic digestion can create methane from agricultural wastes, and biological and catalytic conversion processes can convert methane into products like biomethane, methanol, hydrogen, organic chemicals, single cell protein and bioplastics. Methanotrophic microorganisms can be another biological pathway to produce valuable biomass and value-added bioproducts from methane. A combination of these concepts in a circular agricultural bioeconomy would help to address greenhouse gasses, recycle energy and generate additional economic value from agri-food residues. So, capturing and harnessing agricultural CH_4 as a resource is an emerging opportunity for sustainable, low carbon and resource efficient agriculture.

While agriculture is the primary source of food for the world, it also has critical roles in the emission of greenhouse gases, especially methane (CH_4). Methane escapes through digestive processes, the management of manure from livestock, flooded rice fields and decaying agricultural residues. Methane is a short-lived molecule in the atmosphere, but it is a more potent warming gas, so decreasing the emissions from agriculture will be an important component of climate-change mitigation. Methane, however, should not be an end of itself as a waste gas or environmental burden. It is also a carbon resource of high energy content that can be captured and used to produce valuable products. Anaerobic digestion can recover methane from agricultural wastes and technologies for bio and chimical conversion can convert methane to biomethane, methanol, hydrogen, syngas and other valuable products. Another possible solution is the use of methanotrophic microorganisms, which are microorganisms that are capable of using methane as their carbon and energy source to produce biomass and high-value bioproducts.

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The use of the CH_4 produced in agriculture for useful purposes is then a way to link climate protection with the circular bioeconomy. This is because the process of capturing and using methane can recover energy, value add to farm waste and provide further opportunities for farm and rural businesses. The shift from 'waste management' to 'resource recovery' is an emerging opportunity to consider using agricultural methane as a resource, rather than a greenhouse gas – a real 'green gold' problem.

From emission to opportunity: Capturing agricultural methane

The first step to the transformation of methane into a valuable resource is to capture it before it escapes into the atmosphere. Methane is produced in many places in agricultural systems, such as on farms, manure storage facilities, in rice systems and in organic-waste treatment facilities. These emissions can be collected and directed to energy recovery or additional conversion, as opposed to dispersing. The most mature method is anaerobic digestion, which involves the use of microorganisms to break down manure from farm animals, crop residues and other organic matter under anaerobic conditions. This process generates biogas that is generally high in methane and carbon dioxide gas, and some other gases. The remaining digestate is also a valuable and rich with nutrients organic fertilizer, which can be an additional agricultural benefit. Captured biogas can be utilized directly for cooking, heating or power generation, and can be further purified to remove carbon dioxide, hydrogen sulphide and other impurities to produce biomethane. Biomethane can replace natural gas, which is a fossil fuel, or distributed to appropriate energy systems (where infrastructure allows). So, methane capture is not just about emission reduction, it can be a way to recover energy and nutrients from farm waste. The idea could be expanded even more. After picking up and cleaning up the methane, it can be used as a carbon-rich feedstock for the production of bio-based products, chemicals, and fuels. The transition from "waste to gas" to "waste to methane recovery and use" is an important one in terms of waste management, and represents a step towards moving towards a circular bioeconomy for agriculture.

Methane is more than just a fuel

Although associated with biogas, cooking fuel and electricity generation, the potential for methane is much more than just energy. Methane is a simple carbon-based molecule with a high energy content, carbon-to-hydrogen ratio, which makes it a useful starting molecule for the production of a variety of chemicals at the molecular level. Agricultural methane, therefore, can not only be used as a fuel, but also as a feedstock for a more extensive bioproduct and chemical industry. Methane can be converted to other products via various routes including methanol, hydrogen, syngas and other chemical intermediates. Methanol, for example, can be used as a platform chemical for fuels, solvents and a host of industrial chemicals, hydrogen is becoming a key low carbon energy carrier. A gas mixture of hydrogen and carbon monoxide (syngas) can also be converted to fuels and chemicals. Some very stimulating options are biological approaches. Methanotrophic microorganisms are naturally occurring microorganisms that use methane as a source of carbon and energy. Investigators are trying to utilize them to produce microbial biomass, proteins, organic acids, and biopolymers among other value-added products, from methane. One possible consequence of this method would be the possible ability to run it under less harsh conditions than some of the typical chemical processes and link methane utilization to biotechnology. The true potential is not only to use CH_4 as a fuel but to use CH_4 as a value-added feedstock instead. Agriculture could not only produce renewable energy from captured agricultural methane, but also produce chemicals, materials and biological products, thus providing much more value to an 'emission' resource.

Turning methane into green products

After capturing agricultural methane, the next hurdle will be to find ways of converting this plain gas into more valuable and useful products. Methane is a carbon and a hydrogen source, as a result of which it can be used as a starting material for energy carriers, chemicals and bio-based materials. The pathway to be taken for conversion will depend on the quality of the captured methane, current technology, energy demand and end products. Chemical or Thermochemical pathway is the conversion of methane to intermediate products like Syngas and then to products like methanol, Hydrogen and synthetic fuel. Methanol has a high value because it can be used to produce solvents, fuels and other chemicals in the chemical industry. The use of methane-based hydrogen in emerging low carbon energy systems is also possible, but requires consideration of the overall system including carbon capture and renewable energy. Biological conversion, through the actions of methanotrophic microorganisms, is another potential route. These methane consuming microbes can convert methane into microbial biomass and other products like proteins, organic acids and biopolymers. Their potential to be used for single cell protein and for biodegradable polymers called polyhydroxyalkanoates (PHAs), which may play a role in alternatives to typical petroleum-based plastics is also being investigated. The most appealing aspect of these methods is that they can generate several levels of value from a single emission from agriculture. It can be used directly in a fuel cell to generate electricity, or it can be upgraded to fuels, chemicals, proteins and materials. Such that, agricultural CH_4 can be used as a raw material for a low carbon and circular bioeconomy in which environmental mitigation and economic value creation go hand in hand.

Nature’s methane factories: The role of microbes

The microorganisms called methanotrophs already exist in nature and offer an elegant solution for processing methan. These bacteria and, under certain conditions, archaea are able to obtain carbon and energy from methane. They are part of the natural soil flora and are found in wetlands, sediments and other environments with high concentrations of methane and can therefore be viewed as a biological filter that consumes methane before it enters the atmosphere. Their capacity to transform a greenhouse gas to cell material makes them particularly interesting for sustainable use of methane. Methanotrophs can oxidize CH_4 to methanol and then proceed to oxidize the methanol via a series of enzymatic reactions. The microorganisms are able to incorporate the C-methane into biomass and other products through subsequent metabolic reactions. This microbial biomass could be harvested under controlled cultivation as single-cell protein (SCP) and used as alternative protein source for animal feed, provided safety and regulatory aspects are met. In addition to biomass, methanotrophs are also being investigated as biological production platforms to create value added compounds. Can be used to generate biobased chemicals such as organic acids, biopolymers. For instance, methane carbon may be utilized to make biodegradable polymers called polyhydroxyalkanoates (PHAs), which can serve as substitute for some of the of the conventional plastics. The importance of these microorganisms in relation to climate mitigation and biotechnology is that they connect the two. Methanotrophs are a biological method that can be used to turn methane into useful products rather than just a gas to be captured and burned. These micro methane consumers could be useful in the future methane-to-bioproduct systems, and the use of fermentation technology and process optimization can render an agricultural emission as a biological resource.

From farm waste to circular bioeconomy

There are a lot of organic materials produced in agriculture, such as livestock manure, crop residue, food processing waste etc. that are also biodegradable. So much of this material has been regarded as waste, where some of it breaks down under oxygen deficiency conditions and produces methane gas into the air. The circular bioeconomy would rather look at these materials as valuable resources in the biosphere that can be recovered, converted and reused. The system allows the possibility of using agricultural wastes first in anaerobic digesters to produce biogas that is high in methane gas and a digestate that is high in nutrients. Captured CH_4 can then be directly utilized as renewable energy or upgraded to fuels, chemicals and bio-based products via chemical and/or biological conversion. The digestate may be used as an organic fertilizer in agricultural fields, thereby regaining the nutrients for the crop production and lessening the reliance on synthetic fertilizers. This forms a closed loop of farm waste → methane capture → useful products → agriculture. Carbon and nutrients are retained within the agricultural system whenever possible, instead of being lost to the environment. This can lower GHG emissions and enhance the efficiency of using resources and add value to potentially wasted resources. This shift may bring advantages to farmers and rural populations other than environmental sustainability. Biogas systems can provide local energy, alleviate waste-management issues and offer new business opportunities based on biomethane, fertilizers or novel methane-based products. The circular bioeconomy is an approach that makes sense of the challenges posed by methane emissions from agriculture by connecting them to rural development and resource recovery.

The road ahead: Can methane become green gold?

While the potential for converting agricultural methane from a greenhouse gas to a useful resource is encouraging, there are some barriers. The feasibility of these systems can be heavily influenced by the efficiency of the methane capture, conversion costs, technological complexity, energy requirements and infrastructure. There is a great need for additional research, scale-up and demonstration of technologies for producing high-value chemicals and bioproducts from methane under actual agricultural conditions. Having a truly carbon-negative process is the other key element, especially with regard to energy use and methane escape. Yet, the microbial biotechnology, synthetic biology, catalysis, anaerobic digestion and process engineering have improved considerably and new opportunities are emerging. The conversion of methane to products could become more feasible as improved methanotrophic strains, efficient methane conversion systems, low-energy purification technologies and integrated biorefineries make the process more feasible. Further potential benefits for methane capture and optimisation of agricultural waste-conversion systems could be gained from the use of digital technologies such as sensors and data-driven monitoring. The last chance comes

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when an agricultural system is developed in which nothing valuable, simply discarded. Crop residues and livestock wastes might be sources of feedstocks, methane a source of energy and carbon, and the products a source of new economic opportunities for farmers and rural industries. This vision is to shift the perspective of methane from just an emission to be controlled to a resource to be recovered and transformed. The conversion of agricultural methane to "green gold" is a promising pathway to a more circular and resource efficient agriculture one that is also climate-smart but it will take investment, innovation and good implementation.