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Food without agriculture:

Food from CO2, biomass and hydrocarbons to secure humanity's food supply against global catastrophe

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Abstract

Background: The growing human population requires consistent access to nutritious and sustainable food to thrive. To this end, non-agricultural, closed-environment food production methods can complement agriculture while increasing the resilience of the global food system to climate shocks, biological threats, environmental threats, trade restrictions, and even extreme scenarios such as abrupt sunlight reduction (e.g. from a volcanic winter or nuclear winter).

Scope and approach: This review describes the existing production processes and recent developments in non-agricultural food production, including the activities of companies carrying out established processes and of those developing innovative production processes. The potential of fermentation for production of single cell foods and for biosynthesis of key nutrients, and the nonbiological synthesis of food compounds such as from CO_2 are reviewed in depth. The study has a special focus on potential response to global catastrophic food shocks that disrupt agricultural production.

Findings and conclusions: The enormous potential for food production via key non-agricultural pathways was described and quantified. All macronutrients can be produced by both biomanufacturing and nonbiological synthesis, independently from agriculture, even using CO_2. These technologies are capable of synthesizing all amino acids, as well as the essential fatty acids and multiple vitamins and micronutrients of interest. Many of these pathways are relevant industrially and resilience-wise compared to agricultural pathways due to their potential to produce at either lower cost, improved sustainability, in more extreme conditions and environments (e.g. outer space), or a combination of these. More research and resilience work is urgently needed to realize their potential.

Keywords

Food without agriculture; Global catastrophic risk; Existential risk; Resilient food; Food security; Global Catastrophic Food Failure

Highlights

- All macronutrients and many micronutrients can be produced without agriculture.
- There is potential for sourcing vast amounts of food independently from agriculture.
- Non-agricultural food production is resilient to a set of key food system risks.
- Food without agriculture can reduce global catastrophic risk and existential risk.
- Future work: pilot factories, fast construction and repurposing pilots, open designs.

Abbreviations

Abrupt Sunlight Reduction Scenario (ASRS)

Imperial Chemical Industries (ICI)

National Aeronautics and Space Administration (NASA)

Single Cell Protein (SCP)

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1 Introduction

The current global agricultural system depends on a set of crucial conditions (institutional, abiotic, and biotic) that act as risk factors, including trade restrictions, environmental degradation (pollution, soil erosion), extreme weather events, changing climates, pathogens, and pests (Tzachor et al., 2021). It also depends heavily on steady environmental conditions including sunlight, temperature, and precipitation, all of which could be severely affected by global catastrophes (Denkenberger et al., 2017). Among potential ways to mitigate these risks, non-agricultural food production is underexplored.

The field of non-agricultural food production first gained traction in the 1960s-1970s. Initially, chemical and biochemical production was proposed as an option to deal with mounting pressures to produce enough food for a rapidly growing population (McPherson, 1966), addressing overpopulation concerns of the time. These forecasted pressures on the food system failed to materialize, thanks mostly to the third agricultural revolution, and in turn the idea of a burgeoning non-agricultural food industry also failed to materialize. However, there were successes, including large-scale production of synthetic fats from paraffin wax (García Martínez, Alvarado, et al., 2022), microbial protein from hydrocarbons (Lackner et al., 2022), and large-scale synthesis of vitamins and amino acids such as the chemical synthesis of methionine or the biosynthesis of lysine and vitamin C (Drauz et al., 2007; Eggersdorfer et al., 2012). Regardless, some of these pathways which were competitive at the time were eventually superseded by the decreasing cost of agricultural analogues and were largely forgotten, such as agricultural fats taking synthetic fats out of the market or cheap soy displacing microbial protein feeds.

Now, renewed interest in food without agriculture is coming from various areas. Environmental pressures are leading foodtech companies to reinvigorate the field, finding new ways to reduce food system CO_2 emissions while enabling humanity to feed more people around the world with less water and land use than conventional agriculture. Many routes are being unearthed and developed for food production using CO_2 as main feedstock, reaching towards the ideal of net-zero CO_2 food production. For example, synthetic fat production has potential to fulfill humanity's fat demand at considerably lower CO_2 intensity than many conventional vegetable oils, as demonstrated by (Davis et al., 2023) in their recent work "*Food without agriculture*", inspired by a concept originally developed in the 1940s (García Martínez, Alvarado, et al., 2022). "Air protein", microbial protein obtained via gas fermentation from CO_2 and H_2, has recently seen a surge of companies seeking to commercialize novel alternative protein and cellular agriculture food products (García Martínez, Egbejimba, et al., 2021), based on a NASA concept from the 1960s (Alvarado et al., 2021). Similar processes using methane are driving the construction of large-scale factories around the world to fulfill sustainable animal feed demand (García Martínez, Pearce, et al., 2022). Some researchers are even calling for the mass production of carbohydrates from captured atmospheric CO_2 to address food sector emissions (Dinger & Platt, 2020; O'Brien et al., 2022), which, while economically and energetically questionable, does show the potential of nonagricultural food production for deployment on the scale of gigatonnes per year.

A latent interest in non-agricultural food production for extreme environments is also reemerging from other fronts. Space agencies like NASA are revisiting the development of in-situ food production to efficiently provide food supply in long term missions (Alvarado et al., 2021; García Martínez, Alvarado, et al., 2021; Alvarado et al., 2023) — also fundamental for potential space settlements (Averesch et al., 2023) — such as through NASA's CO_2 Conversion Challenge and Deep Space Food Challenge. DARPA's Cornucopia program is pushing the development of nutritionally complete microbial foods produced from CO_2, water and electricity for military and humanitarian missions. A related idea is applying these technologies for food supply and life support in self-sufficient, isolated refuges (underground, underwater, or extraplanetary) conceptualized to weather catastrophes posing an existential risk to modern civilization or possibly humanity itself (Alvarado et al., 2021; García Martínez, Alvarado, et al., 2021; Alvarado et al., 2023).

Circling back to food security, non-agricultural food production methods have recently been studied as a response intervention to safeguard humanity's food supply in the most extreme agricultural disruption scenarios (García Martínez, Alvarado, et al., 2021; García Martínez, Brown, et al., 2021; García Martínez, Egbejimba, et al., 2021; García Martínez, Alvarado, et al., 2022; García Martínez, Pearce, et al., 2022; Throup et al., 2022), as had been previously proposed by (Y.-H. P. Zhang et al., 2012). They are particularly suited to Abrupt Sunlight Reduction Scenarios (ASRS), defined by a sudden event that projects vast amounts of aerosol material (e.g. a volcanic eruption, asteroid/comet impact, or nuclear war) that stay in the atmosphere for years, causing extensive reductions in solar irradiation, temperature and precipitation, resulting in plummeting agricultural yields (Pham et al., 2022).

This review pays special interest to pathways that leverage non-agricultural resources through industrial conversion to complement traditional food sources and increase the chances that humanity produces enough food in catastrophic scenarios in which industrial manufacturing capacities remain. Compared to agriculture, these closed environment, modular, polycentric food production systems minimize or even remove key risks (Tzachor et al., 2021) such as climate variability (including sunlight dependence as long as sufficient energy can be obtained independently from sunlight), environmental degradation and pollution, pests, pathogens, and trade restrictions. Thus, these systems are more resilient to extreme catastrophic scenarios with partial or total loss of agricultural function such as ASRS, extreme climate change (e.g. abrupt change, runaway change (Richards et al., 2023), or moisture greenhouse effect), or other plant collapse risks from potential future threats, perhaps of biotechnological nature. However, they may be more vulnerable to certain catastrophic events than the current agricultural system, such as those risking a collapse of electrical/industrial infrastructure (Denkenberger et al., 2017).

This article aims to characterize the enormous potential of non-agricultural food production methods for contributing to the global food system by making it more resilient, efficient and sustainable. The list of food production pathways presented here is comprehensive but not exhaustive, capturing all the major pathways capable of producing the largest amounts of food from the major pools of raw materials.

2 Synthesis of food without agriculture

Even in the harsh conditions of an ASRS, many resources that are much more resilient than crops to changes in environmental factors would be available for food production without relying on agriculture, by using industrial technologies (Davis et al., 2023; McPherson, 1966). A summary table of key resources and their potential for food production is given in Table 1. It is expected that even in an ASRS lignocellulosic biomass is a very widely available input for food production (Denkenberger & Pearce, 2014; Throup et al., 2022) not significantly threatened by decomposition rates in most cases (Winstead & Jacobson, 2022). It could make significant contributions to people's diets, especially regarding carbohydrates and minerals, and even proteins and some vitamins for certain types of biomass such as leaves and forages (Siva & Anderson, 2023). Notable quantities of plant waste, food waste and municipal waste may remain available for upcycling to food. Fossil fuels such as natural gas, coal and petroleum can be converted into all three macronutrients (carbohydrates, proteins and fat). Even CO_2 captured from factories or directly from the atmosphere can be converted into multiple types of food, including all three macronutrients, as shown in Fig. 1 (Davis et al., 2023).

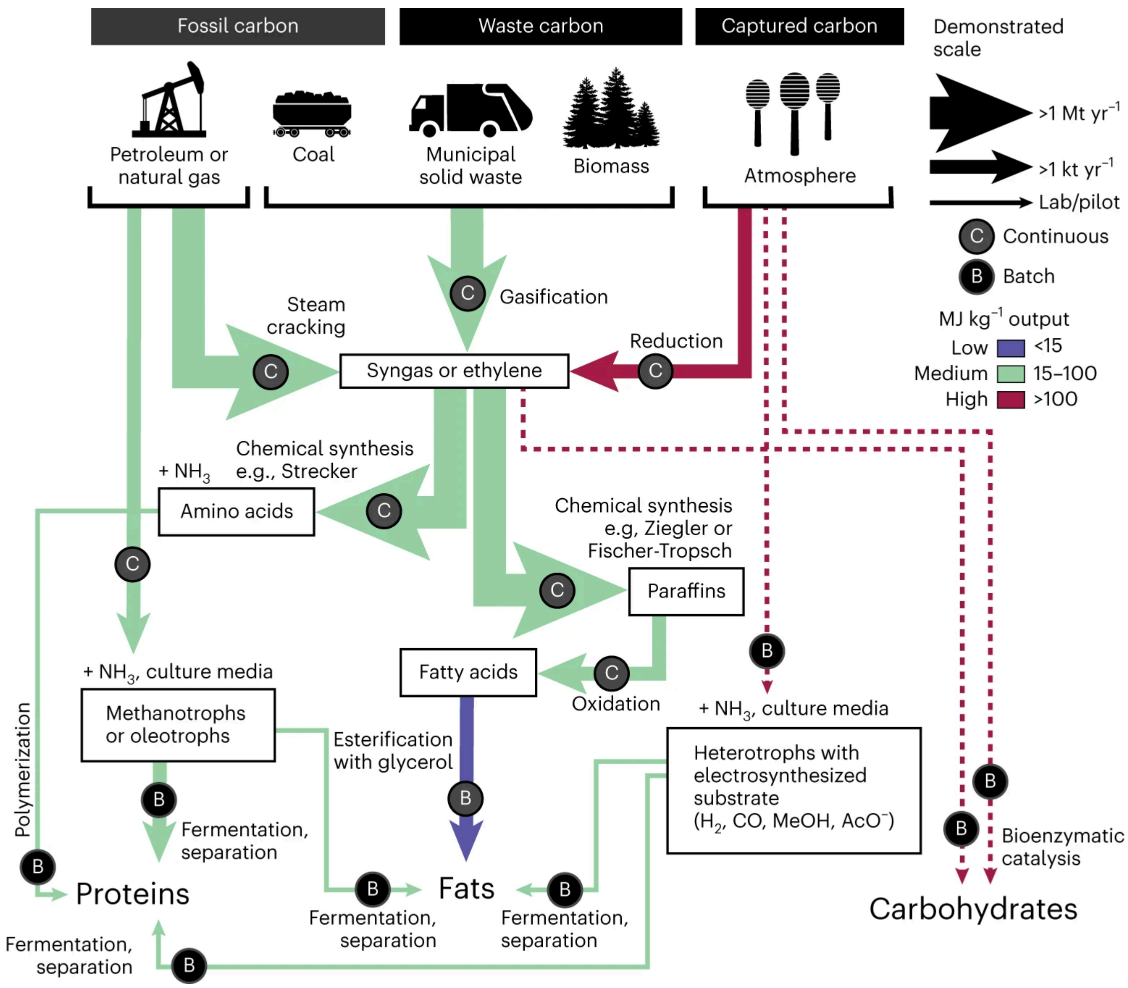


Fig. 1. Schematic of selected pathways to synthesize food without agriculture. Material reprinted from: Steven Davis, Kathleen Alexander, Juan Moreno-Cruz, Chaopeng Hong, Matthew Shaner, Ken Caldeira & Ian McKay, Food without agriculture, *Nature Sustainability*, published 2023 by Springer Nature (CC BY 4.0 license, no changes made). Other relevant pathways (not pictured) include the conversion of biomass to carbohydrates through methods other than gasification (Throup et al., 2022), the conversion of those sugars to proteins, fats, and essential micronutrients through fermentation, or the cultivation of photosynthetic microorganisms.

Table 1. Resources available for industrial conversion of resources independent from agriculture to food, as well as agricultural residues. Includes resource reserves, current production, and an approximate measure of their potential* as a resilient food.

*This potential is illustrated via estimations of the amount of food that could be produced by converting the entire global yearly production of the resource using current technologies, if no other limitations were present. These are only meant as an indication of potential, and do not necessarily imply a recommendation to generate or repurpose entire industrial sectors to food production as a response to catastrophic scenarios, as there may be limitations of industrial, nutritional, or other nature; or better alternatives to be prioritized depending on the situation.

ⱡReferences for production capacity values can be found in the supplementary table.

Resource	**Global reserves**	**Global production per year**	**Food production potential through industrial conversion**
Wood	~900 billion tonne (plant matter, wet) ⱡ	~4 billion m^3/year (roundwood, wet) ⱡ, equivalent to ~1.5 billion tonne/year (dry)	Converting the entire global production of roundwood to sugar would result in the equivalent of 36% of the global population's caloric requirement (Throup et al., 2022). Other nutrients can be obtained, though at lower conversion efficiencies, through various other processes, e.g. feeding pretreated biomass to animals/fungi, or fermenting cellulosic sugar to various nutrients.
Plant residues	N/A	~3.4 billion tonne (dry)ⱡ - might be lower during an agricultural catastrophe	Converting the entire global production of plant residues to sugar would result in the equivalent of 91% of the global population's caloric requirement (Throup et al., 2022).
Natural gas	188.07 trillion m^3 ⱡ	4.09 trillion m^3 ⱡ	Natural gas steam cracking processes enable its transformation to all 3 types of macronutrients (Davis et al., 2023). Converting the entire global production of natural gas to food through single cell protein production results in nearly 3 times the caloric requirement of the global population, or 9 - 15 times the protein requirement (García Martínez, Pearce, et al., 2022).

Petroleum and petroleum products	236.3 billion tonne petroleum †	4.4 billion tonne petroleum †	Petroleum steam cracking processes enable its transformation to all 3 types of macronutrients (Davis et al., 2023). Paraffins derived from oil could be converted into synthetic fats to produce 8% - 17% of the global caloric requirements (García Martínez, Alvarado, et al., 2022). Conversion of oil-derived propylene to glycerol could produce the equivalent of ~16% of the global caloric requirement (García Martínez, Alvarado, et al., 2022).
Coal	1,070 billion tonne †	7.6 billion tonne †	Gasification processes enable the transformation of coal to all 3 types of macronutrients (Davis et al., 2023). Converting the entire global production of coal to food: a) through single cell protein production results in the equivalent of nearly 3 times the caloric requirement of the global population, or 9 - 15 times the protein requirement (García Martínez, Egbejimba, et al., 2021). b) through Fischer-Tropsch and paraffin oxidation, could produce 13% of the global caloric requirement as synthetic fats (García Martínez, Alvarado, et al., 2021).
Carbon dioxide (CO_2)	Reserves can be considered virtually limitless if including industrial and atmospheric carbon capture potential, since the carbon in digested food returns to the atmosphere as CO_2 via respiration. A limited amount is available in CO_2 storage facilities.	230 million tonne (CO_2 commodity market) †	Myriad routes exist for conversion of CO_2 to nutrients. As an example, producing single cell protein from CO_2 and H_2 (obtained via electrolysis), the entire global protein requirement could be covered in 6 years (García Martínez, Egbejimba, et al., 2021). However, since this is an energy-intensive process, like most CO_2 conversion processes, it would require 15-24% of the global electricity capacity (García Martínez, Egbejimba, et al., 2021).

3 Lignocellulosic Biomass as a Sugar Source and a Platform for Food Synthesis

Lignocellulosic biomass is plant dry matter such as corn stalks, wheat straw, leaves, and wood. Its complex polymeric structure composed of cellulose, hemicellulose and lignin makes it indigestible to humans. However, it can be treated with hot steam or biological catalysts to break down the plant matter into simple sugars which can be safely consumed as food, used as an input for animal feed, or upcycled to proteins and other nutrients via fermentation (Throup et al., 2022) — see also the sections on *Biosynthesis of targeted nutrients from sugars (e.g. lignocellulosic glucose)*, *Single Cell Protein from Lignocellulosic Biomass*, and *In vitro BioTransformation*. The major component of this lignocellulose-derived sugar mixture is glucose (from the degradation of cellulose), but the final composition depends on process conditions and the choice of feedstock (Ou et al., 2021; Palà et al., 2022).

To the best of our knowledge, no large-scale lignocellulosic sugar production enterprises have been deployed yet. However, lignocellulosic sugar-based food ingredients have been produced and distributed by companies Renmatix and Comet Bio[1], both of which possess highly efficient patented technologies for the production of lignocellulosic sugar, respectively achieving 85% and 90% of the theoretical yields (Throup et al., 2022). Decentralized low-tech production is also possible, but yields are expected to be notably lower, with some researchers proposing around 30% nutrient extraction ratio for this production style (Siva & Anderson, 2023). In addition, the inner bark of some trees is directly edible, and has been consumed throughout history as a famine food (Turner & Davis, 1993).

Pulp and paper mills, sugarcane biorefineries, corn biorefineries, and breweries have the potential to be repurposed to convert plant biomass into sugar. Doing this would come at a notably lower cost than building new factories, because 84%, 65%, 37%, and 39% of the required equipment for lignocellulosic sugar production is already present, respectively (Throup et al., 2022). In the event of ASRS, if the entire global pulp mill factory capacity were rapidly repurposed for sugar production, that would produce the equivalent of ~9% of the caloric requirements of the global population, and the current global sugar demand could be fulfilled within 1 year after a catastrophe if this technology was deployed en masse (Throup et al., 2022). The cost of these sugars has been estimated at $0.43/kg of sugar mixture, being very affordable at a retail cost of $0.55-0.91 to fulfill a person's daily caloric requirement in ASRS conditions (Throup et al., 2022).

So far no pulp and paper mills, biorefineries, or breweries have been repurposed for producing sugar, to the best of our knowledge. Performing a cellulosic sugar repurposing pilot could help immensely with ASRS response (Throup et al., 2022), by proving to institutional and private decision makers that this food provision method can be deployed to rapidly counter food production yield losses to prevent a global catastrophic food failure. Models and estimates provide only limited catastrophe preparedness.

[1] Personal communication with Loula Merkel from Comet Bio on July 2023: "we have produced several batches of cellulosic dextrose that total around 100 kg"

4 Single cell proteins and oils

Fermentation technologies enable a veritable cornucopia of microbial foods to be produced from a multitude of sources. Gas, liquid and solid fermentation can be used to produce highly nutritious food from inedible plants, fossil fuels, industrial and agricultural byproducts, and even CO_2 from the air as carbon substrates (Woern & Grossmann, 2023; Linder, 2023). These cells can be turned into protein- and fat-rich food ingredients containing a multitude of key nutrients, known as single cell proteins (SCP) (García Martínez, Egbejimba, et al., 2021; García Martínez, Pearce, et al., 2022; Silverman, 2020) or single cell oils if very rich in fats. Fig. 2 shows the schematic of a model SCP powder production process, which describes the vast majority of the processes described in this section. Examples specific to H_2 feedstocks may be found in (García Martínez, Egbejimba, et al., 2021), and for methane processes in (García Martínez, Pearce, et al., 2022).

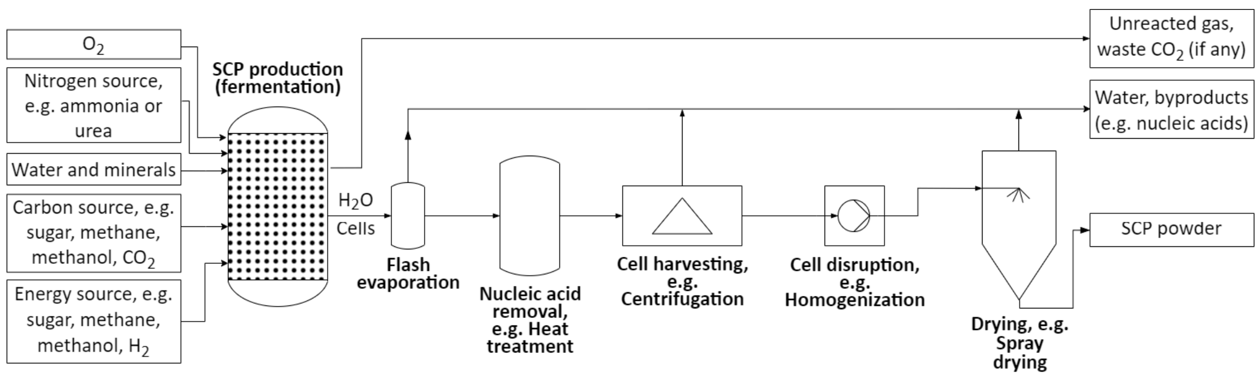


Fig. 2. Process flows and unit operations of an aerobic SCP powder production process through gas or liquid fermentation.

These microbial ingredients might be added to a variety of food products, including solid foods like bread, pasta, and plant-based meats, as well as in liquid food and drinks, such as dairy analogues, protein shakes, or broths (Southey, 2019). SCPs from agriculture-independent feedstocks have yet to be commercialized as food, but the large global yeast products sector with a yearly production of 1.73 million tonnes (FAO & WHO, 2023) provides a very significant precedent for the viability and consumer acceptance of microbial foods, with part of these being used as a food ingredient in many food products or consumed directly as nutritional yeast. They can also be used as animal feeds to circumvent consumer hesitancy, as described in Fig 3. (Linder, 2023) which shows the many direct and indirect possibilities available for food production for humans that single cell foods enable.

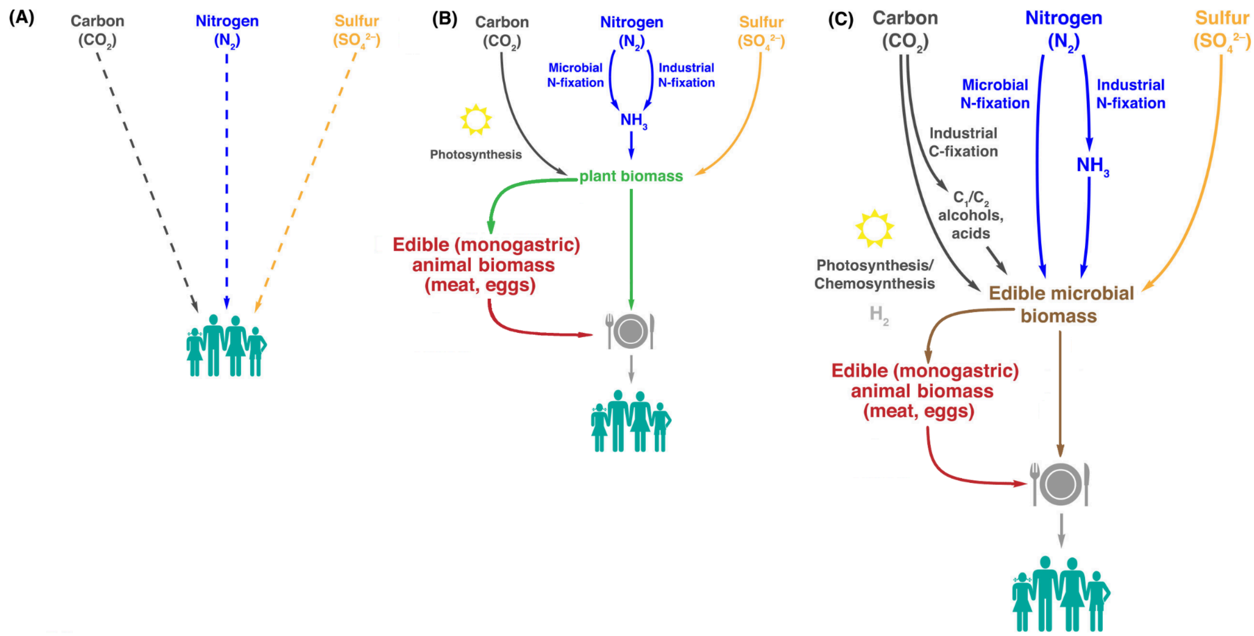


Fig. 3. A biocatalytic view of food production and human nutrition. (A) shows how humans lack the metabolic ability to assimilate the most commonly occurring inorganic forms of carbon (carbon dioxide, CO_2), nitrogen (nitrogen gas, N_2) and sulfur (sulfate, SO_4^{2-}) in nature. (B) shows the traditional concept for agriculture-based food production in which edible plants enable humans to indirectly acquire inorganic carbon, nitrogen, and sulfur, and herbivores enable humans to indirectly access nutrients in inedible plant biomass, or convert edible crops into the animal products that consumers demand. (C) Edible microbial biomass enables humans to indirectly acquire inorganic carbon, nitrogen, and sulfur but without an absolute requirement for photosynthesis, and using the microbial biomass as animal feed can circumvent consumer hesitancy. Material adapted from: Tomas Linder, Beyond Agriculture—How Microorganisms Can Revolutionize Global Food Production, *ACS Food Science & Technology*, published 2023 by ACS (CC BY 4.0 license).

4.1 Gas fermentation

There are myriad production routes to production of single cell protein (SCP) products from gas-fermenting bacteria (Matassa et al., 2020). Four ingredients are required: 1) a carbon source, 2) an energy source (electron donor), 3) a nitrogen source, and 4) an oxygen source (as electron acceptor, unless the process is anaerobic) (García Martínez, Pearce, et al., 2022). As a carbon source, one-carbon compounds (e.g methane, CO_2, CO) are typically provided in the culture medium (Woern & Grossmann, 2023) — this recent review by Woern and Grossman is of note thanks to its in-depth technical discussion of the the challenges and opportunities of gas-based SCP technologies. Two representative examples are discussed in this section.

4.1.1 *Single Cell Protein from Methane (CH_4) - Natural Gas or Biogas*

Methylotrophic organisms enable the conversion of methane to high-protein microbial biomass to be used as food or feed, by growing the microorganisms in bioreactors using methane as carbon and energy source in combination with nitrogen and oxygen sources (e.g. ammonia and O_2 gas). There is huge potential for methylotrophic SCP to make contributions to human food supply by leveraging natural gas and/or renewable biogas resources, both during a global catastrophe and during business-as-usual to enable sufficient food supply for a growing global population (García Martínez, Pearce, et al., 2022). Equation 1 shows the reaction stoichiometry of the process when using ammonia as a nitrogen source (Villadsen et al., 2011).

$$CH_4 + 1.453\, O_2 + 0.104\, NH_3 \rightarrow 0.521\, CH_{1.8}O_{0.5}N_{0.2} + 0.479\, CO_2 + 1.687\, H_2O \quad \textbf{(1)}$$

The two main companies currently developing this technology are Calysta Inc. and Unibio A/S. Calysta, in a joint venture with Adisseo, recently started production in a facility in China capable of producing 20,000 tonnes of protein product each year with intention to scale to 100,000 eventually†, for fish feed uses. Unibio has partnered with Protelux, which operates a plant with an installed capacity of 6,000 tonnes per year of methane-derived single cell protein and allegedly has the potential to scale up to 20,000 tonnes per year†. For comparison, a full-scale 100,000 ton/year plant would produce the equivalent caloric requirement of 620,000 people, or the protein requirements of 2.6 million (García Martínez, Pearce, et al., 2022). Both Calysta and Unibio have plans to build larger factories in other locations, and the sector has other companies working to scale up the technology such as Circe Biotechnologie GmbH, and String Bio Pvt Ltd. Even though methane SCP has yet to be sold for human consumption, all of the companies mentioned in this section are working to change that, having shown interest in producing SCP for the food sector.

The next step in developing this resilient food technology is demonstrating commercial viability for a human consumption market. Drawbacks include the large capital investment needed to build production facilities and the associated high energy usage as well as the high nucleic acid content, requirement of a sterile environment for production and removal of gram-negative bacteria that may produce endotoxins (Lackner et al., 2022).

What makes SCP from methane a promising technology is that there are very large amounts of natural gas available which can be sourced from reservoirs. In addition, stranded natural gas (e.g. currently being flared or reinjected) and biogas could be a significant resource for methane SCP production, considering that global protein requirements could be potentially fulfilled by SCP obtained from these sources alone, as shown in Fig. 4 (García Martínez, Pearce, et al., 2022), without necessarily affecting current natural gas uses. Recent models suggest SCP from methane could fulfill the protein requirements for the entire global population within 2.5 to 4.5 years and could be produced at an affordable wholesale cost of US$1.50-2.50 per kg (dry), costing consumers just ~$2 (retail) to fulfill a person's daily caloric requirement (García Martínez, Pearce, et al., 2022).

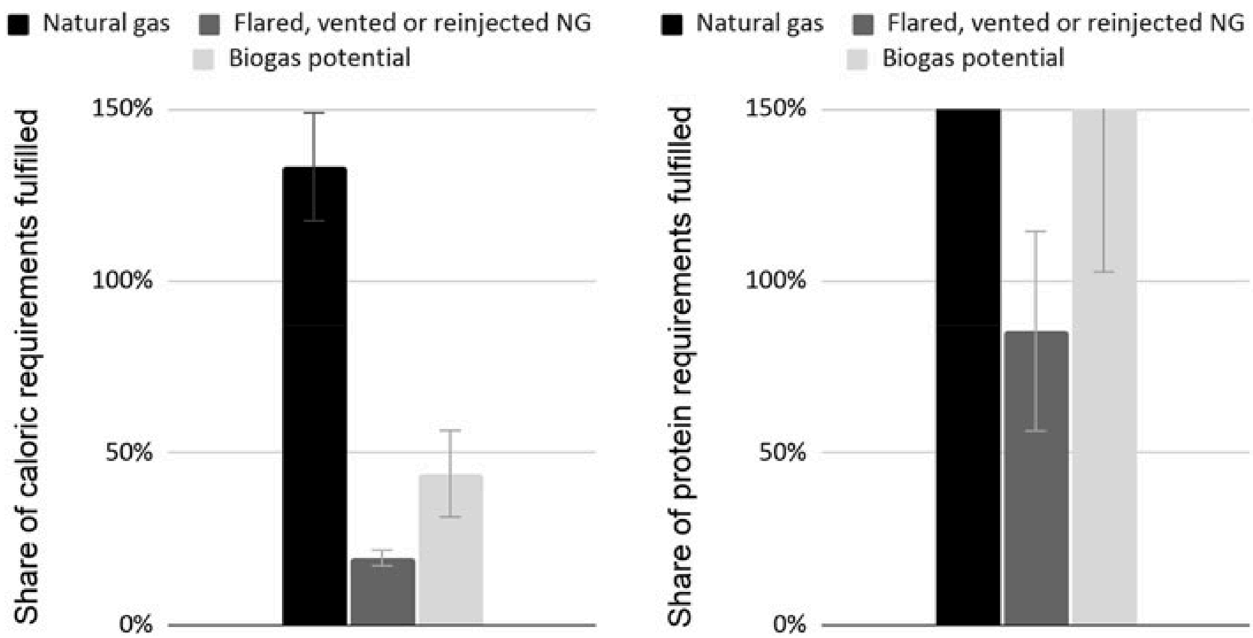


Fig. 4. Share of the global caloric requirements that could be fulfilled by different potential methane sources (left) in comparison with the share of global protein requirements that could be fulfilled using the same sources (right). Material reprinted from: Juan B. García Martínez, Joshua M. Pearce, James Throup, Jacob Cates, Maximilian Lackner, David C. Denkenberger, Methane Single Cell Protein: potential to secure a global protein supply against catastrophic food shocks, *Frontiers in Bioengineering and Biotechnology*, published 2022 by Frontiers (CC BY 4.0 license, no changes made).

4.1.2 *Single Cell Protein from CO_2 and H_2 - "Air Protein"*

Hydrogenotrophic microorganisms can use carbon dioxide (CO_2) as a carbon source and hydrogen (H_2) as an energy source to obtain highly nutritious bulk biomass. These microbes can act as food sources high in protein and micronutrients (especially B vitamins). H_2 SCP could be produced from H_2 sourced from multiple sources, such as water electrolysis or gasification of solid biomass or fuels, while the CO_2 could be obtained from industrial sources, from biomass or fuel combustion or gasification, or directly from the atmosphere (García Martínez, Egbejimba, et al., 2021). Fig. 5 shows a high-level overview of relevant pathways to microbial food production from CO_2 (Linder, 2023), while Equation 2 shows the approximate reaction stoichiometry of the direct CO_2 chemosynthetic process when using ammonia as a nitrogen source, adapted from (Ishizaki & Tanaka, 1990). The use of widely available CO_2 as a carbon source means the resource base for this process is virtually inexhaustible, but current iterations of the technology might suffer from limitations if deployed at massive scale, such as the availability of platinum for electrolyzers or magnesium for microbial media (García Martínez, Egbejimba, et al., 2021).

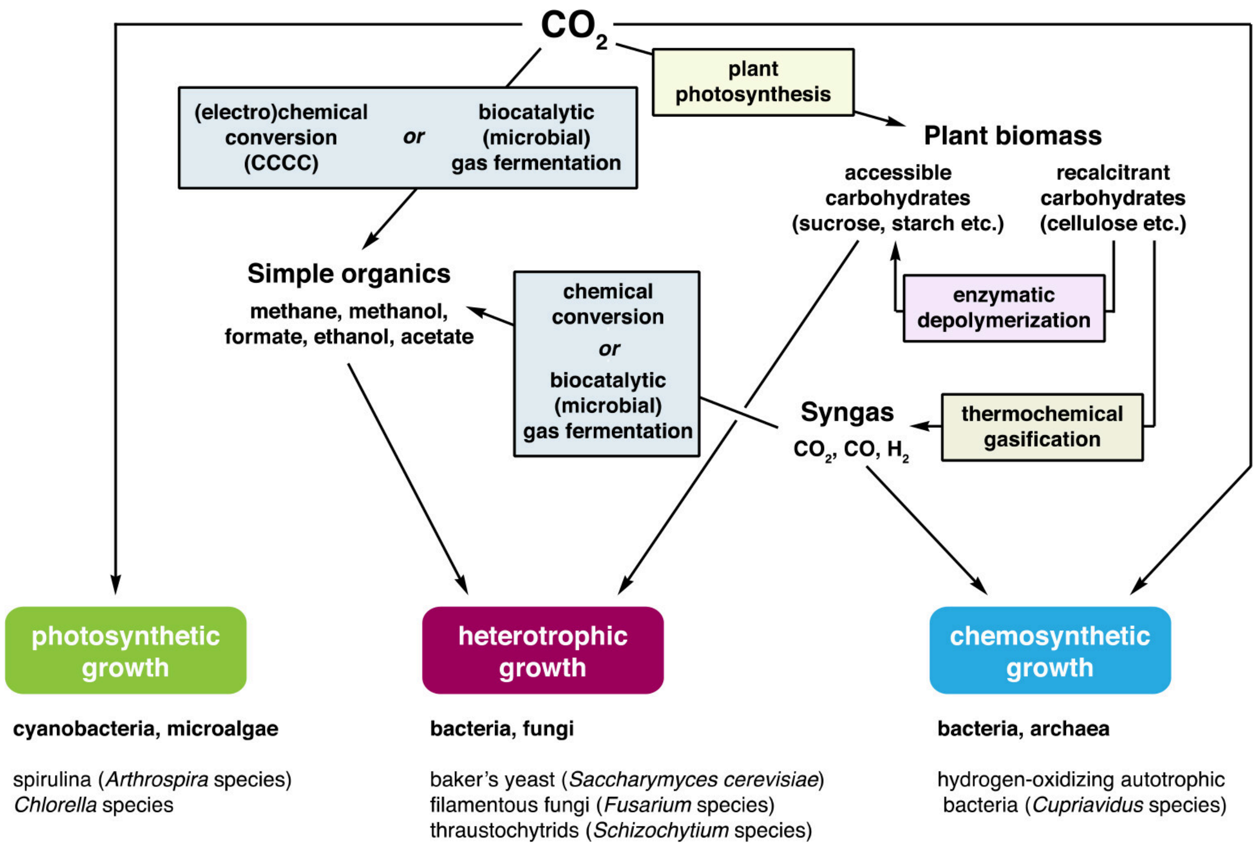


Fig. 5. Possible routes from CO_2 (atmospheric or flue gas) to edible microbial biomass. Material reprinted from: Tomas Linder, Beyond Agriculture—How Microorganisms Can Revolutionize Global Food Production, *ACS Food Science & Technology*, published 2023 by ACS (CC BY 4.0 license, no changes made).

$$CO_2 + 5.222\,H_2 + 1.518\,O_2 + 0.186\,NH_3 \rightarrow C\,H_{1.743}O_{0.462}N_{0.19} + 4.572\,H_2O \quad \textbf{(2)}$$

There are multiple companies working to make single cell protein (SCP) from CO_2 and H_2, including Solar Foods, Air Protein (Kiverdi), NovoNutrients (OakBio), Avecom, Gas2Feed, and Deep Branch; Solar Foods launched its demonstration facility in 2024 (160 tonne/year), the first hydrogenotrophic SCP demonstration scale plant to the best of our knowledge. Deep Branch projects that its first commercial production plant for CO_2-derived single-cell protein will become operational in 2027. However, to date, no company has yet demonstrated commercial viability of this technology mainly due to high capital and operational costs (mainly high electricity requirements).

The potential of this food source to contribute in ASRS is notable, though probably lower than methane SCP due to higher capital costs and a considerable electricity requirement estimated at 32-37.8 kWh/kg SCP for the electrolysis process. For example, if the entire global electricity consumption was instead used to produce SCP from CO_2 via electrolysis, it would produce just over half of the caloric requirement of the global human population (García Martínez, Egbejimba, et al., 2021). The retail cost for customers has been estimated at $2.60-7.40 for fulfilling a person's daily caloric requirement, or $0.45-1.30 to fulfill just the daily protein needs (García Martínez, Egbejimba, et al., 2021).

4.2 Liquid fermentation

4.2.1 Single Cell Protein from Methanol, formate, or acetate as liquid intermediates derived from Natural Gas, Biogas, CO_2, or CO

In the late 1970's, Imperial Chemical Industries (ICI) produced one of the earliest forms of creating SCP under the brand name Pruteen™, a methanol derived protein used in animal feed. It was produced using *Methylophilus methylotrophus* (Macauley-Patrick et al., 2005) in a plant capable of achieving over 50,000 metric tonnes/year through the use of a 600 tonne, 1,500 m^3 airlift fermenter (Westlake, 1986), the largest bioreactor ever built. ICI sold at a market price of 50 cents per pound in 1992 (Weaver, 1991), which inflation-updated to 2024 USD is $2,420/tonne. This Billingham factory cost on the order of £90 million (L. Chen, 2024), which inflation-updated and converted to 2024 USD is approximately $430 million. ICI stopped operations decades ago due to market hurdles (Lackner et al., 2022), and no comparable large-scale liquid fermentation SCP factories have been built as of 2024. However, preliminary analyses for such factories have been made using acetate (a two carbon molecule) as a carbon source, which appears viable at least when using a coupled fermentation approach based on acetogens utilizing the carbon monoxide contained in furnace gas (Vlaeminck et al., 2023). Formate currently appears to have lower potential: a recent meta-analysis proposes that methanol is more advantageous than formate in terms of protein content and carbon yields (Sakarika, Ganigué, et al., 2022); it also has no historical precedent of large scale production, and is generally in an earlier phase of development. As an example, Equation 3 shows the reaction stoichiometry of the process when using methanol as a carbon and energy source, and ammonia as a nitrogen source (Villadsen et al., 2011), where $CH_{1.8}O_{0.5}N_{0.2}$ refers to the formula for protein-rich microbial biomass.

$$CH_3OH + 0.732\,O_2 + 0.146\,NH_3 \rightarrow 0.732\,CH_{1.8}O_{0.5}N_{0.2} + 0.268\,CO_2 + 1.56\,H_2O \qquad \textbf{(3)}$$

Farmless is one company currently looking to commercialize SCP using liquid fermentation of methanol intermediates, ideally sourced from sustainable processes based on renewable feedstocks such as CO_2 or biomass, in contrast with the historical production based on fossil fuels. Other companies such as KnipBio (current capacity 100 tonne/year⸸, for feed additives) are looking to use biofuel plant waste products as an alternative source of methanol and ethanol for SCP production, but this method is of lower relevance to ASRS due to limited feedstock availability in comparison.

Overall these liquid fermentation technologies provide an alternative way of unlocking the potential of multiple widely available feedstocks from both fossil fuels and waste products, separate but related to gas fermentation.

4.2.2 *Single Cell Protein from Lignocellulosic Biomass*

Quorn™, the major SCP product being commercialized directly as food today, is a direct descendant of the historical ICI industrial process for methylotrophic SCP production, with a capacity of 50,000 tonne/year⸸. The most notable difference is that Quorn™ uses sugar as the main feedstock rather than methanol, so it is not independent from agriculture and thus less resilient to loss of agricultural function such as in an ASRS. Using lignocellulosic sugar as a feedstock instead would overcome this issue, for example using Quorn's *Fusarium venenatum* fungus, torula yeast (*Candida utilis*), or Pekilo fungus (*Paecilomyces variotii*). Production costs for these have been estimated at around 5-9 €/kg dry for a 40,000 tonne/year factory operating on straw feedstock, with conversion rates of cellulosic sugar to SCP of 31-50% (Voutilainen et al., 2021). Equation 4 shows the stoichiometry of the process when using glucose as a carbon and energy source, and ammonia as a nitrogen source (Villadsen et al., 2011).

$$CH_2O \; + 0.394\, O_2 + 0.115\, NH_3 \rightarrow 0.577\, CH_{1.8}O_{0.5}N_{0.2} \; + \; 0.423\, CO_2 + 0.65\, H_2O \qquad \textbf{(4)}$$

One company currently working to bring this form of lignocellulose-based SCP to market is Arbiom, with its yeast product SylPro™, planning to have a 10,000 tonne/year factory operational by the end of 2024⸸. Many other companies such as ENOUGH, KnipBio, Hyfé, and iCell have demonstrated the use of sugar- or starch-containing industrial waste streams as an alternative source of sugars for SCP production — ENOUGH reports significant mycoprotein production capacity at 10,000 tonne/year⸸ — but this route is of lower relevance to ASRS due to limited feedstock availability in comparison to the lignocellulose conversion. There also exist alternative processes for SCP production from cellulosic biomass, such as using lactic acid (derived from grass) instead of sugar as a carbon source (Sakarika, Delmoitié, et al., 2022).

To the best of our knowledge, SCP from cellulosic material has been commercialized for animal feed but has not yet been sold for human consumption. However, the large global yeast market serves as a significant precedent, since yeast products are similarly produced via liquid fermentation, though from agricultural sugars. The Soviet Union was thought to have had a significant lignocellulosic SCP industry for animal feed production in the 1980s (CIA, 1984).

4.2.3 *Single Cell Protein from Petroleum-derived Products*

SCPs derived from petroleum products, namely paraffin wax and gas oil, were the first non-agricultural SCPs to be produced at industrial scale, as pioneered by British Petroleum during the 1970s (Shacklady, 1970). British Petroleum's plant had an annual SCP production capacity of up to 100,000 tonnes of *Yarrowia lipolytica SCP* for animal feed, but this and other plants were abandoned due to environmental permit issues and the high input costs (Groenewald et al., 2013). The Soviet Union had a significant paraffin-based SCP industry, claiming to have produced 1.8 million tonnes by 1988 (Greenshields et al., 1990), which rapidly collapsed in the following years (Roffey, 2010). *Yarrowia lipolytica* SCP is recognized as safe for human consumption by the European Food Safety Authority (EFSA NDA et al., 2022), and currently produced by Skotan S.A. in

Poland at a rate of 600 tonnes per year (Groenewald et al., 2013) — though not from petroleum products, but from waste glycerol.

4.2.4 *Microbial Fats from Lignocellulosic Biomass*

Yarrowia lipolytica is a very versatile microorganism, which can be used to produce dietary fats including omega and essential fatty acids (H. Liu et al., 2021), which are fundamental for human health and are often not found in sufficient quantities in the resilient foods proposed for ASRS response (Pham et al., 2022). Lignocellulosic sugar enables cultivation of Yarrowia for fat production independently from agricultural sugars. Another method utilizes plant fiber which would be turned into a pulp, and then the cellulose would be digested directly by *Cystobasidium oligophagum* to produce the fats (Vyas & Chhabra, 2017). The two essential fatty acids have been synthetized at significant concentrations: *Cystobasidium oligophagum JRC1* was found to contain linoleic acid content of 24.2% of total fatty acids (Vyas & Chhabra, 2017), while modified *Yarrowia lipolytica* yielded α-linolenic acid at a concentration of 28.1% of total fatty acids (H. Liu et al., 2021).

There is potential that in the event of a global catastrophe, pulp and paper mills, biorefineries, and breweries could be quickly repurposed to convert plant biomass into key lipids by installing the relevant equipment (Throup et al., 2022) including SCP producing bioreactors. For example, using lignocellulosic biomass as the carbon source by first converting it to sugars (Throup et al., 2022) or using it to grow cellulose-digesting microbes (Vyas & Chhabra, 2017) to produce lipids.

To the best of our knowledge, the methods described for production of nutritionally relevant lipids are not currently used for food production, although Dupont used to produce a Yarrowia-derived omega-3 rich product at scale for direct human consumption called New Harvest™ (Xie et al., 2015). In addition, the startup Äio is looking to commercialize single cell oils made from sawdust as substitutes for unsustainable vegetable oils (palm, coconut), with products rich in omega fatty acids. Further research into better understanding and optimizing the bioprocess to convert cellulosic material into microbial fat and scale up costs as well as conducting human safety trials would help make this resilient food technology a better option for catastrophe response.

4.2.5 *Single Cell Protein from Peat*

Peat is a solid carbonaceous material originating from decaying organic matter, which can be hydrolyzed into a mixture (peat hydrolysate) that some microorganisms can use as a carbon source. This process has been demonstrated for the production of nutrient-rich biomass at laboratory scale (Taskila et al., 2016), but to the best of our knowledge has not been commercialized or tested for food uses, or even analyzed for economic viability, thus requiring extensive study to characterize its resilient food potential. However, considering that there are over 4 million km^2 of peatlands containing 550 billion tonnes of carbon (Harris et al., 2022) — more than all of Earth's forests — this method should be noted.

4.3 Solid-state fermentation

Solid-state fermentation, referring to fermentation processes using a solid substrate with absence or near absence of water, has also been used for the production of potential food compounds. An example is the saccharification of solid lignocellulosic biomass by cellulolytic enzyme-producing fungi, which has been proven on sugarcane bagasse (Farinas, 2018). This could enable 1-step synthesis of lignocellulosic sugar, which might serve as a source of food or an input to fermentation processes.

A different but related idea that was proposed as potentially useful for lignocellulosic biomass conversion in ASRS is direct digestion of woody material using cellulose digesting bacteria, followed by flushing out the sugar produced (Denkenberger & Pearce, 2014). This would synergize with other resilient food sources since mushrooms could feed on the lignin byproduct for this process and ruminants could feed on what is leftover from the mushrooms (Denkenberger & Pearce, 2014). However, this idea is speculative and no proof of concept exists as of now.

A more unorthodox example is the production of SCP on plastic substrates. Proof of concept has been achieved by growing microorganisms on a Polyethylene terephthalate (PET) plastic substrate using a combination of chemical and biological processing by a team exploring the feasibility of obtaining SCP from plastic (Schaerer et al., 2022). They estimated that "*If all PET waste (32 million tonnes per year) was converted with 100% efficiency into human food, we could supply ~4% of the global carbon consumption [of food]*" (Schaerer et al., 2022).

4.4 Photosynthetic microorganism cultivation (SCP)

There exists a large diversity of microorganisms capable of fixing CO_2 through photosynthesis using sunlight or other sources of light energy, some of which have considerable potential as food sources. These organisms are similar to hydrogenotrophs in that they both use CO_2 as their carbon source, meaning they are both autotrophs, but they use sunlight instead of H_2 as an energy source, meaning they are photoautotrophs rather than chemotrophs. Microalgae are the most commonly produced and already established as a food source, but other organisms proposed for SCP production include purple phototrophic bacteria (Capson-Tojo et al., 2020).

Microalgae are single cell photosynthetic organisms which grow in water using CO_2 as a carbon source. They grow naturally in aquatic environments, but can be cultivated in either closed photobioreactors or artificial open ponds, or a hybrid of both. Closed reactors are able to control the precise conditions (i.e. temperature, light, CO_2 levels) for the microalgae while providing constant agitation to incorporate the CO_2. Open ponds are a larger, and more scalable production method, but are less efficient in terms of quality due to lower control of growing conditions (Narala et al., 2016).

Microalgae are an excellent source of protein, fatty acids, and essential vitamins including A, B12, D, and E (Chamorro-Cevallos, 2015). It also can grow in areas of varying pH levels and can grow with minimal light exposure (Difusa et al., 2015), with even the most extreme ASRS conditions allowing for significant open pond microalgae productivity. Microalgae have very fast growth rates, are more efficient than plants at converting sunlight into energy, and have minimal biomass waste (Okoro et al., 2019; Perrine et al., 2012). Microalgae's role as a source of omega-3 fatty acids in oceanic trophic chains is so important that (Moomaw et al., 2017) have called for "cutting out the middle fish" by eating omega-3 rich microalgae like *Nannochloropsis oculata* instead of fish.

Naturally occurring spirulina (*Arthrospira platensis*, a type of cyanobacteria) was harvested and consumed by the Aztecs, and still is around Lake Chad (Barone et al., 2023). Global annual production of microalgae was 93,000 tonnes in 2010, but declined to 56,000 in 2019, with spirulina being the only species cultivated in significant quantities (J. Cai et al., 2021). (Greene et al., 2022) estimate that using the top 5% most suitable areas near 20 km of the coast for microalgae cultivation could produce 587.9 megatonne/year, more than the global protein demand projected for 2050.

However, high unit costs currently are a considerable obstacle for microalgae foods. Cost ranges from 100 $/kg when using closed reactors to 10 $/kg using open raceway ponds (Oostlander et al., 2020). Significant work is required to bring production costs down, most notably optimization of cultivation processes and strain productivity (Dolganyuk et al., 2020). Most notable in this area is the benchmarking work of (Klein & Davis, 2023) based on experimental efforts, which estimates the minimum production costs of microalgae biomass at ~$0.70 per dry kg, and projects cost reductions to ~$0.50/kg dry by 2030 (for a 20% dry, non-food-grade product assuming n-th plant economics and lowest-cost methods).

The resilient food potential of microalgae under resource-constrained scenarios of catastrophe response is probably limited to the pond production method. In terms of energy efficiency, the photobioreactor method has considerably lower electricity-to-calories efficiency than alternative processes such as hydrogenotroph SCP that can produce at higher than 10% efficiency (Alvarado et al., 2021), with state of the art microalgae photobioreactor systems having 2.4% efficiency (Tzachor et al., 2022).

5 Microbial cell factories for food production

Fermentation technologies not only enable the production of nutritionally-rich single cells, but also the exploitation of microorganisms to convert renewable resources and upcycle waste products into food products (Choi & Lee, 2023). In comparison with the previous section discussing consumption of whole cells or their component parts, this section discusses the use of microorganisms as cell factories for food production, in which they are used to synthesize food compounds without being consumed themselves, or the biological compounds that enable other food production routes such as enzymes.

These methods are at varying levels of technology and economic readiness and would require different impulses for their development and application where appropriate. More modeling research is needed to characterize this potential in both business as usual and catastrophe response scenarios, by estimating production costs, scalability, and ramp-up speed. Demonstrating scale-up and food safety are the main avenues of practical work for the development of these methods as a resilient food technology.

5.1 Biosynthesis of essential nutrients from sugars (e.g. lignocellulosic glucose) through precision fermentation

Microorganisms have incredible potential for synthesizing key nutrients of relevance to avoiding malnutrition, which is particularly relevant in catastrophes that limit crop growth like ASRS. Glucose, such as that obtained from lignocellulosic biomass, can be used to produce all 3 macronutrients, most major vitamins, and all 9 essential amino acids (Choi & Lee, 2023).

Many of these production routes are at various early stages of development, but some represent very mature industries. For example, vitamin C biosynthesis from glucose was performed at a scale of 140,000 tonnes/year in 2018 (Demain & Sánchez, 2019). Lysine — an essential amino acid — is currently produced at very large scales via *Corynebacterium glutamicum* using glucose or sucrose as a feedstock. Production facilities synthesize an average of 100,000 to 400,000 tonne/year, to supply a market size of 2.2 million tonnes (2016 values) (J. Liu et al., 2022), at prices around $1.5/kg for L-Lysine HCL (Ploegmakers, 2024). Researchers are actively looking into alternative feedstocks for lysine production that do not compete with human food sources, such as algae-based mannitol (J. Liu et al., 2022), which is of relevance to ASRS. Progress in genetic engineering could be relevant to enabling more favorable feedstocks (Wendisch et al., 2016).

5.2 Biosynthesis of food from carbon dioxide

5.2.1 *Lipid biosynthesis from CO_2 and H_2*

Hydrogenotrophic bacteria can be used not only for direct consumption as SCP, but also as platforms for the synthesis of nutrients via gas fermentation (from CO_2 and H_2) in aerobic bioreactors. Recent advancements in genetic engineering allow for the production of multiple compounds relevant to industry and space exploration (Nangle & Ziesack, 2022; Dunn et al., 2023; Averesch et al., 2023). Of note is their capacity to manufacture crucial nutrients such as triacylglycerides with high energetic efficiency (Nangle & Ziesack, 2022). This has yet to be commercialized as a food source, but a startups looking to do so is Circe Bioscience Inc[2].

5.2.2 *Amino acid biosynthesis from CO_2 and H_2*

Hydrogenotrophic archaebacteria can be used to produce free amino acids via an anaerobic process, using CO_2 as a carbon source and H_2 as an energy source (Taubner et al., 2023). These amino acids may be purified and used directly as food ingredients, or polymerized into peptides or protein macromolecules for food (Dondapati et al., 2020). Although this process has not yet been commercialized, one startup working to leverage it for food production is Arkeon Biotechnologies.

5.2.3 *Microbial Electrosynthesis of Acetic Acid and Fatty Acids from CO_2*

Microbial electrosynthesis refers to the use of electroactive microbes as biocatalysts in bioelectrochemical reactors for the synthesis of compounds of interest. One such example is the generation of carboxylic acids from CO_2, although so far only short- and medium-chain fatty acids have been synthesized from this method, which are not as nutritionally relevant as long-chain fatty acids. (García Martínez, Egbejimba, et al., 2021) studied the potential of electrotrophs to convert CO_2 and water into acetic acid — typically consumed as the main component of vinegar, with a caloric content of 3.49 kcal/g (Greenfield & Southgate, 2003), comparable to sugars by mass. The overall reaction for acetic acid synthesis can be described by Equation 5 (Christodoulou et al., 2017).

$$2CO_2 + 6H_2O + 8e^- \rightarrow CH_3COOH + 4H_2O + 2O_2 \qquad \textbf{(5)}$$

Despite its very high energy efficiency as a calorie generation method, between ~15-20% in terms of power to food when using carbon capture (Alvarado et al., 2023), this technology is severely limited for the catastrophe response application, and is not recommended over alternatives. Current forms of the technology produce compounds that do not provide key nutrients and cannot make large caloric contributions to the diet, while hydrogenotroph SCP produces key nutrients at comparable unit cost and energy efficiency. Production costs are also higher than other foods in

[2] U.S. based company, not to be confused with the Austrian company Circe Biotechnologie GmbH (see section on single cell protein from methane)

this work, at $2.60-6.50/kg wholesale (García Martínez, Egbejimba, et al., 2021). Realizing the potential of microbial electrosynthesis for resilient food production would require developing similarly efficient methods to use it for long chain fatty acid, protein, or micronutrient synthesis. Alternatively, the acetic acid could be used as an intermediate to grow more relevant nutrients, including plant nutrients, using hybrid inorganic-biological systems (Hann et al., 2022; Zheng et al., 2022), but this would greatly reduce overall energy efficiency compared to direct consumption of microbial electrosynthesis products.

6 In vitro BioTransformation (ivBT)

In vitro BioTransformation produces biocommodities using in vitro synthetic enzymatic biosystems, consisting of specific combinations of natural enzymes, artificial enzymes, biomimetic or natural coenzymes, or artificial membranes or organelles. This is a third approach to food biomanufacturing separate from enzymatic biocatalysis (e.g. enzymatic lignocellulosic sugar synthesis, see Section 3) or the cell-based fermentation approaches described in sections 4 and 5. ivBT is characterized by the use of artificial enzymatic pathways and artificial electron transfer chains to overcome certain limitations of natural biological systems and achieve high product selectivities and yields (Y.-H. P. J. Zhang et al., 2023).

The most notable potential application of ivBT for resilient food production without agriculture is the synthesis of starch and glucose from cellulose, first described by (You et al., 2013). It has undergone significant cost reductions in the last decade and was recently improved upon by (Xu et al., 2023), who describe a broader novel method that allows for one-pot conversion of lignocellulosic biomass to artificial starch and SCP. Starch has even been synthesized via ivBT from CO_2 (T. Cai et al., 2021). The first industrial application of ivBT is the one-pot synthesis of the inositol micronutrient, a high-value added food product and nutraceutical, currently performed at 10,000 tonne/year by Sichuan Bohaoda[4]. It can be synthesized via ivBT from cellulose, independently from agriculture (Han et al., 2023).

This existing large-scale application of ivBT indicates potential for large-scale food production applications. However, to the best of our knowledge no economic analyses describing the costs of producing food from lignocellulosic material at scale using ivBT are available. Further process development is needed for ivBT-based conversion of lignocellulosic material to macro- and micronutrients, in order to reduce costs and scale up the process. Technoeconomic analyses should be performed to compare its affordability and catastrophe response potential to comparable options like lignocellulosic sugar production and fermentation approaches.

7 Chemical synthesis of food

Biological organisms are not strictly necessary for food production. Fundamental nutrients such as vitamins and amino acids are routinely produced from commodity chemicals. Chemical building blocks such as CO_2, syngas, or ethylene can be converted into various types of carbohydrates (Davis et al., 2023). This section focuses on the provision of food through purely nonbiological pathways, reviewing relevant methods in which nutrients have been synthesized using chemical processes that do not involve living organisms.

7.1 Synthesis of food from hydrocarbons

7.1.1 Chemical Synthesis of Vitamins

Industrial synthesis of vitamins is probably the most established form of nonbiological nutrient synthesis, starting in 1934 and becoming a large sector with both significant production volume and market value (Eggersdorfer et al., 2012). Vitamins A, B1, B5, B7, and E are currently synthesized nonbiologically in industrial quantities from widely available petrochemicals[3]. Vitamin B6 is synthesized from common chemicals which are typically obtained from agricultural products but can be synthesized nonbiologically as well. Vitamins C and B2 can be synthesized nonbiologically but fermentation is the current industry standard. Vitamin A is synthesized at over 7,500 tonnes/year (Bonrath et al., 2023), B1 at 4,000 tonnes/year (Demain & Sánchez, 2019), and B6 at 2,500 tonne/year (Demain & Sánchez, 2019).

7.1.2 Chemical Synthesis of Amino Acids

There are three most common techniques for synthetic amino acids production: fermentation via engineered microbes, enzymatic catalysis (refer to *The potential of biosynthesis through microbial conversion of lignocellulosic biomass* section), and direct chemical synthesis. Methionine, glycine, and aspartate/asparagine can be synthesized nonbiologically (Drauz et al., 2007). Amino acids produced in this manner can be used in a free form for direct consumption, to supplement other sources of food such as wheat to fulfill protein completeness requirements (McPherson, 1966), or they could be polymerized into proteins (Dondapati et al., 2020).

DL-Methionine is the most massively synthesized, with a yearly global production capacity of exceeding 1.6 million tonnes by 2020 (Neubauer & Landecker, 2021). It is produced from common chemicals (sulphur, methanol, ammonia, propylene, sulphuric acid) and was traded at an average price of ~$2.50/kg in Europe and China during 2022-2023 (Ploegmakers, 2024). Glycine has been chemically synthesized in the order of over 10,000 tonne/year, from chloroacetic acid with ammonia.

[3] Some common synthesis routes in industry: B1 is produced nonbiologically from petrochemicals (commonly acrylonitrile or malononitrile). B5 is produced nonbiologically from petrochemicals (isobutyraldehyde and formaldehyde). B7 is produced nonbiologically from petrochemicals (fumaric acid). A is produced nonbiologically from petrochemicals (isoprenal and prenol, via isoprenol, itself derived from isobutene and formaldehyde). E is produced nonbiologically from petrochemicals (m-cresol, acetylene, and acetone), but a new fermentation process recently took over, with an annual output of 30,000 tonnes (Ye et al., 2022). B6 is produced chemically from ethanol and diketene (typically from acetate), which are typically obtained from agricultural products but can be synthesized nonbiologically as well (Eggersdorfer et al., 2012).

7.1.3 *Fats from hydrocarbons or from CO_2 (Paraffin oxidation process)*

A synthetic butter or oil substitute can be produced by converting n-paraffins via paraffin oxidation which ruptures the alkanes creating "synthetic" fatty acids (García Martínez, Alvarado, et al., 2022). These paraffins may be obtained, among other sources, as a common petroleum processing byproduct, as a byproduct of coal liquefaction (Fischer-Tropsch process), or they may be synthesized from chemical building blocks such as CO_2 or natural gas. The derived free fatty acids may then be esterified with glycerol into triacylglycerides to form a butter-like product, which was consumed as a food product during a fat shortage in 20th century Germany, as obtained from Fischer-Tropsch paraffin byproducts (García Martínez, Alvarado, et al., 2022). In 1978, production of "synthetic" fatty acids in Eastern Europe was over 500,000 tonnes (Fineberg, 1979). Due to higher costs of synthetic fatty acids produced from petroleum compared to agrichemicals, production rapidly declined and they are no longer manufactured (Anneken et al., 2006). However, the startup Savor Foods has recently started production of synthetic butter substitutes from CO_2 with the intent to commercialize as a food product, with a reported energy to calories efficiency of 26.5% (Davis et al., 2023), and has already produced prototypes using paraffin derived from petroleum, natural gas, and CO_2[4]. CO_2 emission accounting models indicate that the paraffin oxidation process can even have lower emissions per unit of product than butter and common agricultural oils such as Brazilian or Indonesian palm oil (Davis et al., 2023).

Models indicate that this resilient food technology could be scaled relatively rapidly to produce the equivalent amount of food to 100% of the global fat requirements in about 2 years (García Martínez, Alvarado, et al., 2022). Wholesale production costs have been estimated at $1.30-4.70/kg for factories constructed using 24/7 construction, or a retail cost for customers of just $0.75-2.70 to fulfill a person's entire daily caloric requirement (García Martínez, Alvarado, et al., 2022). Compared to business-as-usual, synthetic fat could become an economically competitive source of fat in the event of an ASRS that causes agricultural fat prices to skyrocket. However, a limitation of this process is that it only produces saturated fats (García Martínez, Alvarado, et al., 2021), which are often recommended by dietary guidelines to be consumed as less than 10% of total energy intake (USDA & USDHHS, 2015).

Further scale up is needed as well as resolving major uncertainties regarding production potential, capital expenditure, food safety, transferability of labor and equipment construction (García Martínez, Alvarado, et al., 2022).

7.1.4 *Glycerol from propylene*

Glycerol, also known as glycerin, is a sugar alcohol (a type of carbohydrate) with a sweet taste that is often used as a food ingredient in baked goods (Bagnato et al., 2017). Glycerol can be chemically synthesized from propylene, a mass produced petroleum product (Bagnato et al., 2017). Propylene is currently produced on very large scales, but it has yet to be used widely for synthesis of

[4] Personal communication with Kathleen Alexander and Ian McKay of Savor in January 2024: Proof of concept for synthetic butter production has been achieved from petroleum wax, natural gas synthetic wax, and CO_2-synthetic wax.

food-grade glycerol, which is now obtained from vegetable oils and fats — a more economical route in the current market conditions.

The process can operate at a molar conversion yield of 76.5% (García Martínez, Alvarado, et al., 2022), which in terms of mass works out to ~1.67 units of glycerol produced per unit of propylene consumed (this is despite the unreacted propylene, because the glycerol molecule has a notably larger mass). At this conversion rate, the global production of 150 million tonnes of propylene would allow for production of up to 251 million tonnes of glycerol, equivalent to ~16% of the global caloric requirement. However, more research is needed to prove the potential of synthetic glycerol as a resilient food technology, such as pilot studies and fast factory construction pilots. Equation 6 shows a simplified overall reaction for the process (García Martínez, Alvarado, et al., 2022).

$$C_3H_6 \ + \ 2\,Cl_2 \ + \ H_2O \ + 2\,NaOH \ \rightarrow \ C_3H_8O_3 \ + \ 2\,HCl \ + \ 2\,NaCl \qquad \textbf{(6)}$$

7.1.5 *Chemical Synthesis of other Carboxylic Acids*

Acetic acid, citric acid, lactic acid and malic acid are organic acids with three important characteristics in common: they are used as common food additives for their acidulant properties, they have estimated calorie contents between 2.3-3.5 kcal/g (Greenfield & Southgate, 2003), and they can all be synthesized nonbiologically. Acetic acid can be efficiently produced through non-biological electrochemical methods, at an estimated electricity to calories efficiency of over 25%, based on a reaction energy consumption of 33.71 kJ/g acetate (Hann et al., 2022). Citric acid can be produced through Bis(chloromethyl) ketone, typically derived from propylene, but this petrochemical route is not economically competitive with biological synthesis in the current market (Max et al., 2010). Lactic acid can also be synthesized from petrochemical resources, via ethylene (Lebarbe, 2013). Similarly, malic acid can be synthesized from butane through maleic anhydride (Cornils et al., 2014). Mature industries for the production of all these carboxylic acids exist in the world today, but they generally use more economical biological methods, a situation which an agricultural catastrophe such as an ASRS could reverse.

7.2 Chemical synthesis of carbohydrates from carbon dioxide

Glucose, glycerol and propylene glycol can be synthesized from CO_2, water, and electricity using electrochemical and thermochemical reactions (Cestellos-Blanco et al., 2022). The power-to-food conversion efficiencies of this route are estimated at 10-21% (García Martínez, Alvarado, et al., 2021; Kouidri & Taylor, 1970) using current technologies, although the theoretical efficiency is much higher at 31-73% (Dinger & Platt, 2020). The challenges and opportunities of these technologies are discussed in-depth in a recent review by (O'Brien et al., 2022).

The main inputs for these technologies, CO_2, water, and electricity, are widely available and easily accessible given the right equipment. The CO_2 can be obtained from industrial fuels or directly from the atmosphere (García Martínez, Egbejimba, et al., 2021). Water is generally used to obtain the H_2 needed for this reaction (sourced from splitting water electrolysis), but the H_2 can also be obtained via gasification of solid fuel or steam methane reforming (García Martínez, Egbejimba, et al., 2021). Regarding the intense energy consumption of the process, (O'Brien et al., 2022) estimates a nominal cost of the energy needed for the process of $1.15/kg of artificial carbohydrate. This can vary widely depending on the energy cost, between $0.71-2.86/kg for electricity costs between $50-200/MWh.

Fig. 6 shows a simple scheme of proposed synthesis routes from CO_2 to digestible carbohydrates; expanded synthesis schemes can be found in (García Martínez, Alvarado, et al., 2021)'s Figure A1 and (O'Brien et al., 2022)'s Figure 3. The routes discussed here use formaldehyde as an intermediate for nonbiological synthesis of sugar, but longer routes through CO_2-based methanol or propylene are also possible — see (O'Brien et al., 2022) and the section on *glycerol from hydrocarbons*.

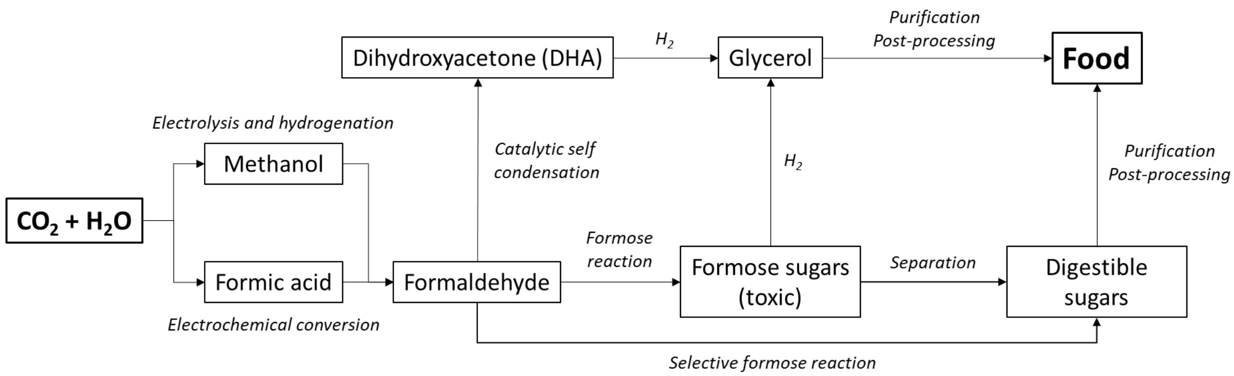


Fig. 6. Selected electrosynthetic routes for digestible sugar production from CO_2 and water, adapted from (García Martínez, Alvarado, et al., 2021).

7.2.1 *Sugars from CO_2 and H_2*

The well-known formose reaction has for a long time enabled the conversion of CO_2-derived formaldehyde into a complex, mildly toxic sugar mixture containing racemic combinations of C4-C7 sugars. Recently, a long-sought innovation has enabled the selective synthesis of digestible sugars from the formose reaction thanks to the development of a highly selective chiral catalyst by Air Company, obtaining "primarily d-glucose and d-ribose along with d-fructose as a minor component" (García Martínez, Alvarado, et al., 2021).

The Air Company process takes CO_2 (from the atmosphere) and H_2 gas (through electrolysis of water) as inputs into a tubular, fixed-bed flow reactor which, with the help of a catalyst, hydrogenates the CO_2 into alcohols and water, which are then distilled to produce methanol. Next, the methanol is dehydrogenated into a formaldehyde, which then undergoes a polymerization reaction to produce simple sugars. This process won first place in the 2021 NASA CO_2 conversion challenge by demonstrating the synthesis of a mixture of carbohydrates composed of right handed enantiomers (García Martínez, Alvarado, et al., 2021), the digestible non-toxic variety, using a selective chiral catalyst. Of note is their pilot methanol production facility (first part of the sugar process), which can process CO_2 at a maximum of 350 tonne/year (C. Chen et al., 2022).

Another participant in the NASA challenge, team SSwEET used CO_2-derived glycolaldehyde to autocatalyze sugar formation by reacting with the formaldehyde, both obtained through electrosynthesis (Cestellos-Blanco et al., 2022), but the sugars produced are racemic and thus not recommended for consumption (García Martínez, Alvarado, et al., 2021).

Similar to lignocellulosic sugar, sugars derived in this way can also be used as a platform chemical for the production of various other nutrients of interest as described in the following sections. The main drawback is these technologies are at an early stage, and further work to optimize the process for large scale production is needed.

7.2.2 *Glycerol from CO_2 and water*

Glycerol can be synthesized from CO_2 and water via formaldehyde and DHA efficiently through electrochemical means (García Martínez, Alvarado, et al., 2021). There is still no proof of concept or food safety studies for this technology. However, by 2022, systems to convert CO_2 to formic acid are estimated to have reached pilot scale (Masel et al., 2021). Equation 7 shows an overall chemical reaction from CO_2 and water to glycerol via DHA (see Fig. 6), disregarding side reactions. Further research is needed to prove the concept, reduce the energy usage, prove the food safety, and the scalability to characterize the potential of the method as a resilient food in the event of ASRS.

$$3CO_2 + 4H_2O \rightarrow C_3H_8O_3 + 3.5O_2 \qquad (7)$$

8 Discussion

The technologies described in this work are distributed across a wide range of technology readiness levels and market readiness levels. As we have seen, some are now being developed to produce new economically competitive sustainable products (e.g. various single cell proteins, synthetic fats from CO_2), while others lost their market niche to agricultural analogues (e.g. synthetic fat and methanol single cell protein) or are not ready to compete with them in current market conditions (e.g. sugars from cellulosic biomass or synthesized from CO_2). Some are at very early stages of development (e.g. carbohydrates from CO_2), while some others have been produced at industrial scale (e.g. synthetic fat and methane single cell protein) or form the basis of mature markets (e.g. methionine synthesis and vitamin C and lysine biosyntheses).

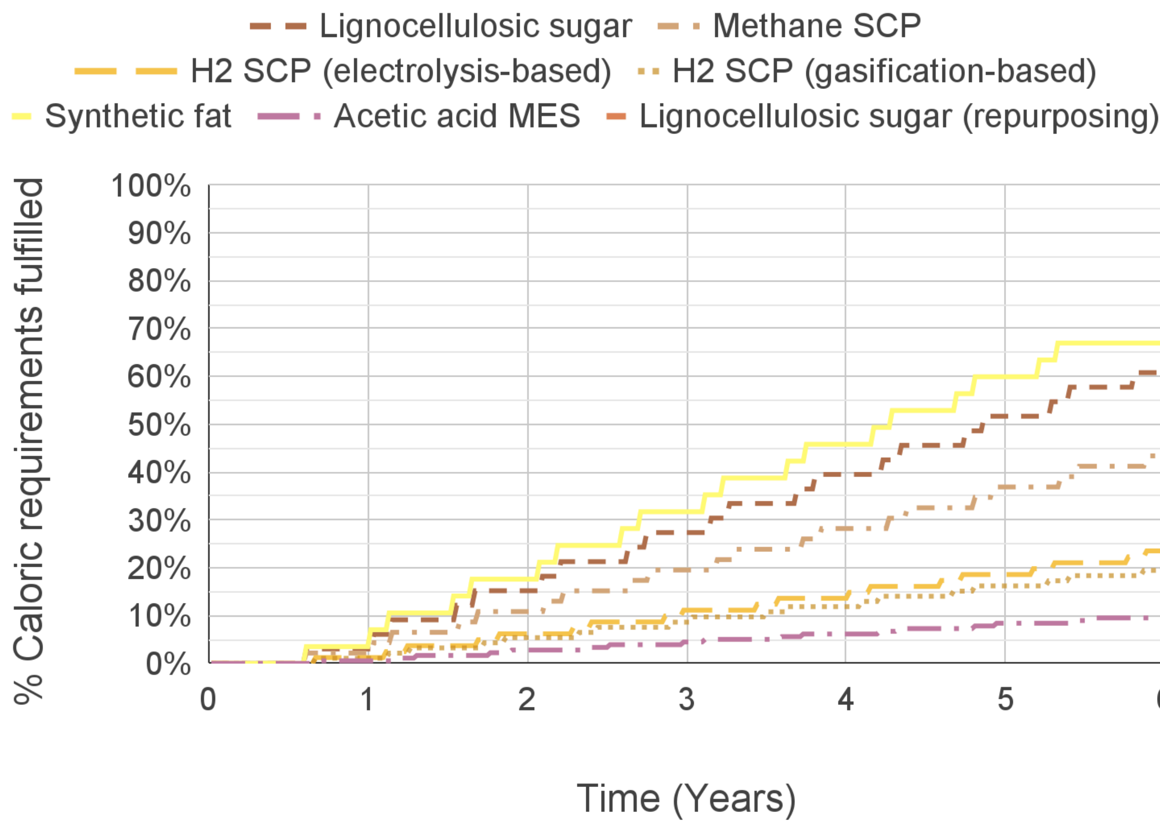
Displacing unsustainable agricultural and ocean products is one way for these technologies to have a major positive impact through industrial implementation. To give some examples: alleviating 1) the pressure that high CO_2-intensity proteins such as beef and other meats, as well as some oil crops, put on the environment by using fermentation technologies (e.g. SCP for proteins and synthetic fats for oils and butter), 2) the pressure that fishing puts on ocean biodiversity (e.g. displacing fishmeal using low-cost SCPs, and displacing omega-rich fish products using microbial fats), 3) the pressure that palm oil puts on forests through chemical synthesis of fats, and 4) the enormous suffering that animal agriculture inflicts in nonhuman animals using these technologies to displace animal agriculture products. However, more research is needed on the environmental impacts to deploy these sustainably, e.g. life cycle assessments.

The large-scale deployment of gas-based SCPs, synthetic fats, and lignocellulosic sugar (as well as derived nutrients) should be given special attention thanks to their potential to produce significant quantities of valuable nutrients using widespread raw materials with relatively low resource intensity (especially lower fertilizer, water, and land use per unit of food produced than industrialized agriculture), and potentially with lower CO2 emissions depending on implementation. In terms of increasing resilience to agricultural catastrophes, piloting the repurposing of existing infrastructure for the production of these foods would be particularly valuable.

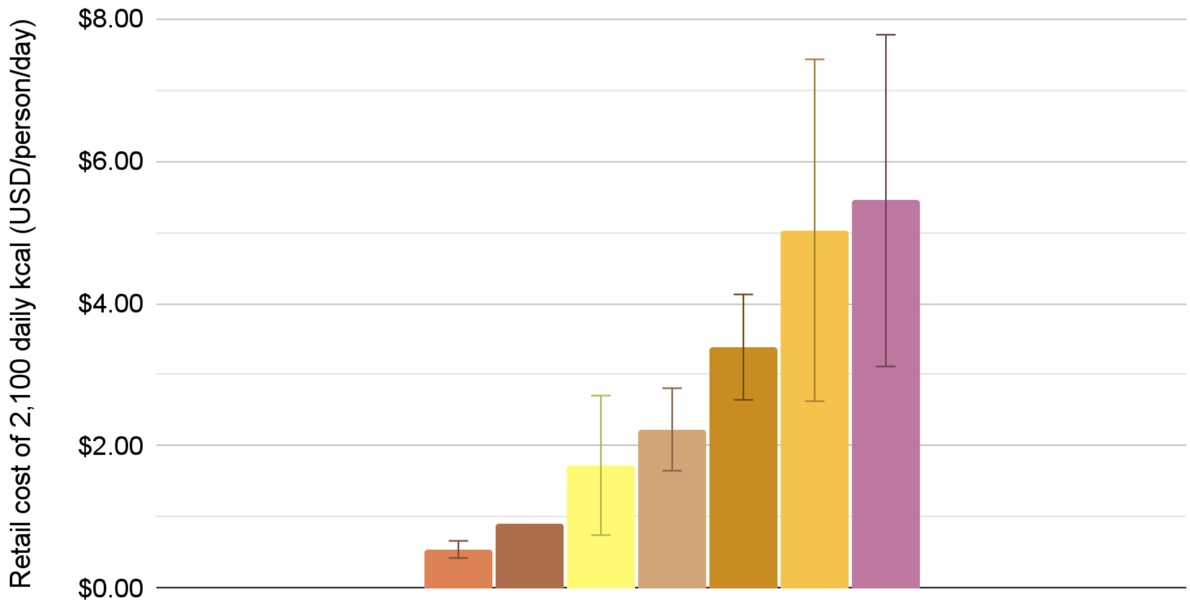
Further work will focus on the market and technology readiness level of these technologies, but some developments that many of the technologies would benefit from include: conducting food safety and nutritional studies which verify that the novel foods created from these technologies are safe and nutritious for humans and/or animals, working on regulatory approval of the foods to ensure catastrophe readiness, investing more into research and process optimization, primarily for the resilient food technologies that are in the earliest stages of development, and increasing government support by dedicating public resources towards resilient food technologies to speed up their development.

8.1 Future work on resilient food synthesis

This section focuses instead on the future work in the field of production of food without agriculture to increase the resilience of food systems. Estimating the potential for emergency response of all the different food production methods described in this work is an important first step for prioritization. García Martínez et al. calculated the production cost and ramp-up speed at which various technologies could be deployed as a response to an abrupt sunlight reduction catastrophe such as a nuclear winter (García Martínez, Egbejimba, et al., 2021; García Martínez, Brown, et al., 2021; García Martínez, Alvarado, et al., 2022; García Martínez, Pearce, et al., 2022; Throup et al., 2022). The results are given in Fig. 7, and the methodology for ramp-up speed estimation based on historical construction speed data and 24/7 construction speed methods is described in the cited articles and in particular detail in the supplementary material of (García Martínez, Egbejimba, et al., 2021). Using 24/7 construction (46% capital cost increase from regular), it would take an estimated capital of $4.2 trillion to deploy enough lignocellulosic sugar plants to produce the equivalent of the entire calorie requirements of the global population (Throup et al., 2022). Synthetic fat from petroleum is estimated to require $0.2-0.9 trillion to produce the equivalent of the global fat requirements, assuming 15% of dietary intake from fat (García Martínez, Alvarado, et al., 2021). Methane SCP would require $6.1 trillion for fulfilling caloric requirements and $1.2-1.9 trillion for fulfilling global protein requirements (García Martínez, Pearce, et al., 2022), while H_2/CO_2 SCP would require $7.1-15.8 trillion for calories and $1.4-4.8 trillion for protein (García Martínez, Egbejimba, et al., 2021). These expenditures are considered financially feasible in a global catastrophic scenario, given that national governments spent at least $17.2 trillion in stimulus packages during the COVID-19 pandemic, a catastrophe of considerably smaller magnitude than an ASRS. The models estimate that the limitation in mass deployment of these food sources is instead on available construction capacity and labor availability. Performing similar analyses for all the other non-agricultural food sources would benefit humanity's emergency response capabilities to agricultural catastrophes.



Lignocellulosic sugar
Methane SCP
H2 SCP (electrolysis-based)
H2 SCP (gasification-based)
Synthetic fat
Acetic acid MES
Lignocellulosic sugar (repurposing)
% Caloric requirements fulfilled
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
1
2
3
4
5
6
Time (Years)



Retail cost of 2,100 daily kcal (USD/person/day)
$8.00
$6.00
$4.00
$2.00
$0.00

Fig. 7. a) Ramp-up speed of various non-agricultural food production sources for deployment using 24/7 construction after a global agricultural catastrophe. Values are given in terms of the amount of caloric requirements of the global population (at 2,100 kcal/person/day) fulfilled over time by the factory deployment, on a 2020 basis, for the average of expected capital cost of the factories, and assuming a low food waste value of 12%. Note that the values are given for each food source assuming all industrial resources are used for each process, and not distributed among the different options. b) Retail cost to consumers for fulfilling the equivalent of one's daily calorie requirements, estimated as twice the breakeven production cost. Data from (García Martínez, Egbejimba, et al., 2021; García Martínez, Brown, et al., 2021; García Martínez, Alvarado, et al., 2022; García Martínez, Pearce, et al., 2022; Throup et al., 2022).

These ramp-up forecasts can be improved in many ways. Using chemical equipment supplier data at the component level (reactors, vessels, heat exchangers, etc.) to analyze the possible bottlenecks that could arise during mass-scale deployment in a more precise way than the abovementioned simple models based on the current manufacturing expenditures of related industries. Labor availability and retraining analyses would help understand the degree to which qualified labor availability may be a limitation to fast response in a catastrophe. Construction time forecasts can be improved by using higher quality historical data as a reference class, and ideally real data from 24/7 construction pilots carried out for each of these methods. Pilot testing of 24/7 construction methods for food without agriculture factories would also allow for better capital cost estimates and food cost and price estimates. The latter would also benefit from the inclusion of these food production methods in economic equilibrium analyses of catastrophic scenarios, such as the recent analysis of (Hochman et al., 2022) for a nuclear war scenario.

In addition, there are many steps that could be taken now to increase societal resilience to abrupt agricultural catastrophes using non-agricultural food sources. The abovementioned capital intensive pilot tests could be enabled by funding from governmental science grantmaking institutions or capital investors to enhance societal resilience, in particular 24/7 construction and repurposing pilots for lignocellulosic sugars (e.g. converting a paper mill to a biorefinery) and single cell proteins (e.g. from methane) seem to be the most promising for emergency resilience at the moment. Demonstrating the capacity of these methods to be deployed quickly in the event of a global catastrophe and/or preemptively building some of the infrastructure now would likely help enable a sufficiently fast catastrophe response in general. For example, after the onset of an ASRS, policymakers and lawmakers should encourage private industry to construct and repurpose factories that produce non-agricultural resilient foods that can be used as food for humans, feedstock for biofuel, and/or feed for animals. Industry may need funding assistance or other incentives from policymakers to successfully construct the number of factories needed in a catastrophe.

Collecting information from interviews with industry experts working on these technologies would serve to better estimate labor requirements and ramp-up speed feasibility, and ideally there should exist resources such as guides written by them on building and operating the plants. Generic plant front-end engineering design packages, ideally open-source and perhaps developed by academia, would serve as a blueprint to enable companies around the world to respond to a catastrophe faster and more effectively. Governmental risk management institutions could generate coordinated response plans for the materials and labor deployment to a collection of pre-approved sites to enable a sufficiently rapid emergency response. Emergency response plans could include communication materials to be used in a catastrophe for improving the awareness of and knowledge on these technologies to the public and researchers (García Martínez, Pearce, et al., 2022). Repurposing studies (and ideally pilots) for characterizing the potential of existing industries for non-agricultural food production, such as was done by (Throup et al., 2022), could help enable a more effective, rapid, and economical emergency response.

8.2 Ethical considerations

Most of these technologies are currently under development, with their potential still being explored, but some are already calling for their mass deployment at the gigatonne scale (Dinger & Platt, 2020; O'Brien et al., 2022). As development continues, it will become increasingly important to understand the tradeoffs between food security and environmental benefits versus potential downsides of mass application. Further research is needed at the intersection of food without agriculture and ethics, including environmental, economic, and health impacts, before these systems are developed to the point where they could fulfill a significant share of humanity's food intake. For example, the research field on the health impacts of ultra-processed foods (while still rife with research challenges and lacking sufficient high-quality evidence) is studying the possibility that more intensively processed foods increase the risk of obesity and other adverse health outcomes, even after controlling for relevant factors (e.g. the increased energy intake these foods tend to produce) (Gibney & Forde, 2022). Considering how the synthetic foods described here are by definition heavily "processed", researchers developing them should pay attention to future findings in the field of nutrition. As these technologies develop the potential to displace agricultural production, it becomes more relevant to look into the effects on agricultural livelihoods and overall employment, including uncertainties such as if this would economically impact agricultural workers, and to what degree. Other ethical concerns warranting future research include the importance of perceived "naturalness" in food to consumers, and the justice component of historical transitions from traditional to industrial processes, see (Davis et al., 2023). In addition, while requiring less resources such as fertilizer, water, and land than agriculture, non-agricultural food technologies may require larger quantities of mined materials and metals than industrial factories of agricultural fertilizer and machinery.

From an even longer-term perspective, (Holt, 2021) explored the question of whether it would be desirable for humans to "cut the umbilical cord" linking humanity to the Earth's biosphere (referring to ecological services such as traditional food production), if the capacity to do so is developed. She argued that doing so is "morally undesirable unless done in the service of reducing negative impacts on the biosphere", because of the rare potential of Earth's biosphere to help humanity recover from a global civilizational collapse or possibly even recreate intelligent life in case of human extinction, and also because of its conceivable intrinsic value. She further argues that synthetic food production is a particularly noble form of techno-adaptation, to the degree that it can help preserve the biosphere, a form of "conscious decoupling".

9 Concluding remarks

The enormous potential of the myriad methods to produce food without agriculture is demonstrated by the many selected methods described in this work. More than the entire global demand of sugar can be provided through conversion of lignocellulosic biomass without increasing wood removals, and this could also be done through repurposing existing industries such as paper mills. It could also be used as a platform for most nutrients of relevance to human diets through fermentation technologies, such as all 3 macronutrients, all amino acids (including all nine essential amino acids), the essential fatty acids, and multiple vitamins and micronutrients of interest. CO_2 is more energetically expensive as a starting material, but is virtually endless and can be converted into all 3 macronutrients, with models suggesting that it could be used to fulfill the entire global human protein demand through single cell proteins in just 6 years. Single cell protein from natural gas or biogas can be produced at lower costs and capital expenditures at even faster rates. Models suggest that converting hydrocarbons to fat substitutes (synthetic oil or butter) can be done rapidly and at an affordable cost to alleviate supply losses during an agricultural catastrophe, in some cases with lower CO_2 emissions than some common agricultural products such as butter and Brazilian or Indonesian palm oil.

These closed-environment, polycentric food production systems minimize or remove key risks such as trade restrictions, environmental degradation (pollution, soil erosion), extreme weather events, changing climates, pathogens, and pests. Developing these and other food without agriculture technologies can make great positive contributions to the sustainability and resilience of food systems, land use change, food supply in extreme environments such as space missions and humanitarian missions, and food supply in extreme conditions such as agricultural catastrophes and potentially existential catastrophes.

More research and resilience work is urgently needed to realize the potential of many technologies for production of food without agriculture, such as process development and optimization or food safety and nutritional studies. In particular, for increasing resilience to global agricultural catastrophes, pilot testing of these technologies at relevant scales, pilots for repurposing existing industries for food production, and pilots of rapid construction (24/7) methods applied to them would be of considerable help, as well as generating open source front end engineering design packages and rapid deployment plans and operational guides.

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Supplementary material - Table S1: Production capacity values

ⱡ Values marked with a dagger in the main text are referenced here:

Commodity	**Value**	**Reference**
Wood, global reserves	~900 billion tonne (plant matter, wet)	(Throup et al., 2022; Bar-On et al., 2018)
Wood, global production per year	~4 billion m^3/year (roundwood, wet), equivalent to ~1.5 billion tonne/year (dry)	(FAO, 2021)
Natural gas, global reserves	188.07 trillion m^3	(Ritchie et al., 2022)
Natural gas, global production per year	4.09 trillion m^3/year	(Sönnichsen, 2023a)
Petroleum, global reserves	236.3 billion tonne	(Ritchie et al., 2022)
Petroleum, global production per year	4.4 billion tonne/year	(Sönnichsen, 2023b)
Coal, global reserves	1,070 billion tonne	(Ritchie et al., 2022)
Coal, global production per year	7.6 billion tonne/year	(IEA, 2021)
Carbon dioxide (CO_2), Global production per year	230 million tonne/year (CO_2 commodity market)	(IEA, 2019)
Propylene, Global production per year	150 million tonne/year	(Statista, 2023)
Single cell protein from methane, Calysta, yearly production capacity of factory	20,000 tonne/year	(Settelen, 2022)
Single cell protein from methane, Unibio, yearly production capacity of factory	6,000 tonne/year	(Leth & Polyakovsky, 2021)
Single cell protein (mycoprotein), Quorn, yearly production capacity of factory	50,000 tonne/year	(Butler, 2018)

Single cell protein from lignocellulosic biomass, Arbiom, yearly production capacity of factory (expected)	10,000 tonne/year	(Arbiom, 2022)
Single cell protein from sugar- or starch-containing industrial waste streams, ENOUGH, yearly production capacity of factory	10,000 tonne/year	(Watson, 2023)
Single cell protein from methanol- or ethanol-containing industrial waste streams, KnipBio, yearly production capacity of factory	100 tonne/year	(Chen, 2024)
Single cell protein from hydrogen and CO2 gasses, Solar Foods, yearly production capacity of factory	160 tonne/year	(Sinisalo, 2024)
Inositol synthesis, Sichuan Bohaoda Biotechnology corporation, yearly production capacity of factory	10,000 tonne/year	(AHA International, 2023)

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