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Potential of microbial electrosynthesis for contributing to food production using CO_2 during global agriculture-inhibiting disasters

Juan B. García Martínez [a,*], Michael M. Brown [a], Xenia Christodoulou [a,c], Kyle A. Alvarado [a,b], David C. Denkenberger [a,b]

[a] Alliance to Feed the Earth in Disasters (ALLFED), Fairbanks, AK, USA
[b] University of Alaska Fairbanks (Mechanical Engineering and Alaska Center for Energy and Power), Fairbanks, AK, 99775, USA
[c] School of Business and Engineering Vaud, Yverdon-les-bains, Canton of Vaud, Switzerland

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ABSTRACT

A sun-blocking global catastrophic risk (GCR) such as a nuclear winter could completely collapse the agricultural system. Producing alternative foods through methods requiring little to no sunlight has been identified as a cost-effective response to these types of GCRs. This preliminary techno-economic assessment evaluates the potential of acetic acid (AA) derived from carbon dioxide (CO_2) via microbial electrosynthesis (MES) as an alternative food source for GCRs. Production and retail costs are estimated using net present value analyses for catastrophe and non-catastrophe scenarios. Based on nonstop (24/7) facility construction, the speed of food production ramp-up is estimated from capital expenditures using a reference class forecasting correlation. Potential production bottlenecks are assessed via a global resource requirement analysis. In regular conditions, the production cost of AA produced via MES is estimated at \$1.83–\$5.20/kg (dry). MES production ramp-up is expected to fulfill less than 1% of global human caloric requirements by the end of the first year after the catastrophe. The retail cost of AA produced via MES in catastrophe conditions is estimated at \$6–\$15/kg (dry). Potential bottlenecks to ramp-up include high electricity use and platinum dependency, which could be palliated via alternative processes based on gasification or bioelectrodes. AA from MES is not currently recommended as an alternative food for GCRs, because it is significantly more expensive and resource intensive than alternatives. Future research may change this, and could perhaps even enable MES as a sustainable food production method outside of catastrophes, given its potential for CO_2 utilization.

1. Introduction

Alternative methods for food production are needed for events that would inhibit the conventional agriculture that supports civilization. Such events are considered global catastrophic risks (GCRs), which pose threats to humanity's well-being and potentially even to civilization's existence (Turchin and Denkenberger, 2018). One subset of GCRs, food-related global catastrophes, refer in this study to events on Earth that in many cases would obscure sunlight and reduce global temperatures, thereby vastly reducing humanity's ability to grow crops (Denkenberger and Pearce, 2015). The goal of this work is to strengthen resilience and response for possible future, food-related GCRs. Resilience and response strengthening have been proposed as facets of a robust defense against existential risk (Cotton-Barratt et al., 2020), as they could potentially reduce existential risk factors.

Different food-related global catastrophes would inhibit conventional agriculture via distinct mechanisms. A full-scale nuclear war between the United States and Russia (Barrett et al., 2013), or perhaps involving China (Denkenberger et al. to be published) is a relatively likely event, where sunlight would be blocked by smoke rising from smouldering cities and entering the stratosphere; a global nuclear winter could result from such a scenario. One model of this representative global catastrophe estimates that for 6–10 years, only half of the usual amount of sunlight would reach the Earth's surface, causing an approximately 10 °C maximum global temperature drop (Coupe et al., 2019). This would prevent crops that are not cold tolerant from growing outdoors, with the number of cold-tolerant plants that could grow outside being further reduced by drastic reductions in growing season length outside of the tropics. A related subset of GCRs would indirectly affect food systems by disrupting industry and/or electricity (Cole et al., 2016), and would require different solutions (Denkenberger et al.,

* Corresponding author.
E-mail address: juan@allfed.info (J.B. García Martínez).

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Abbreviations

Acetic acid (AA)
Global catastrophic risk (GCR)
Microbial electrosynthesis (MES)
Acetic acid produced via microbial electrosynthesis (MES-AA)
Short-chain fatty acids (SCFAs)
Capital expenditure (CapEx)
Operational expenditure (OpEx)
Carbon dioxide (CO_2)
Direct air capture (DAC)
Net present value (NPV)
Front-end loading (FEL)
Techno-economic assessment (TEA)
Tonne or metric ton (t)

2017). Other significant GCRs with food-related consequences include a supervolcanic eruption, asteroid or comet impact, super-weed, super-pest, or super-bacterium (Denkenberger and Pearce, 2015). In a severe global food-related catastrophe, there would be inadequate opportunity for adaptation; without previous preparation, the disruption in food production could cause hundreds or even thousands of millions of people to starve.

Seemingly intuitive alternatives to conventional agriculture, namely large-scale food stockpiles and crops grown with artificial light, face major obstacles: it would be extremely expensive to store sufficient volumes of food, and significant amounts would be rendered unavailable to humanity during the storage period, exacerbating existing food insecurity (Denkenberger et al., 2019). Artificial light photosynthesis is extremely energy intensive, predominantly due to the need for precise control of the growth environment (Alvarado et al., 2020); even if all of the current global electricity demand were directed to growing crops with this method, it could feed only about 5% of the global population (Denkenberger and Pearce, 2014) at an extremely high cost (Denkenberger et al., 2019).

For other alternative food solutions to render artificial light photosynthesis and additional food storage unnecessary in a global catastrophe, the solutions would need to provide food to the global population in a rapid, cost-effective, and energy-efficient manner. These effective alternative foods would be comparatively inexpensive to produce, so in expectation they would cost-effectively save lives globally (Denkenberger and Pearce, 2016) and regionally (Denkenberger and Pearce, 2018).

Several promising solutions could meet these standards of speed, cost, and resource intensity. Low-tech greenhouses could grow certain crops (Alvarado et al., 2020), and global seaweed production could be ramped up (Mill et al. to be published). Industrial resources not directly involved in food production could be redirected towards either building new production plants for alternative foods, or repurposing existing factories for food production (Throup et al., 2020) via lignocellulosic sugars, for example. Single cell proteins produced from methane (García Martínez et al., 2020) or from CO_2 and hydrogen (García Martínez et al., 2021) show significant promise for fulfilling the global population's protein requirements. Sufficiently high demand for the end food product could economically justify this diversion of resources. Other alternative food sources that have been investigated and do not rely on factories include expanded fishing (Scherrer et al., 2020), and leaf-protein concentrate production (Pearce et al., 2019), as well as mushrooms and insects (Denkenberger and Pearce, 2015).

This work aims to characterize the potential of microbial electrosynthesis (MES) as an alternative method to produce food during global catastrophes. In MES, electroactive microbes are used as biocatalysts for synthesis reactions in electrochemical cells (Prévoteau et al., 2020). To the best of our knowledge, carboxylic acids are the only nutritionally rich products that can be directly obtained via MES from CO_2. Only short- and medium-chain fatty acids have so far been synthesized (Vassilev et al., 2018), and of these only acetic acid (AA) has been produced in significant amounts (Dessì et al., 2021). We have focused solely on AA as a food source for global catastrophes.

MES is a potential food production method for sun-blocking GCR scenarios, because it can use feedstocks not directly dependent on agriculture and sunlight, such as water and industrial or atmospheric CO_2. Both CO_2 capture (Rahimpour et al., 2020) and utilization (Styring et al., 2015) are rapidly expanding areas of research, due to their value in sustainable chemical production and energy integration. MES as a CO_2 utilization method currently faces significant challenges such as low titers, high operating costs and the achievement of industrially relevant production rates at an acceptable energy efficiency (Prévoteau et al., 2020). However, MES could also hold significant potential for production of value-added chemicals independently of fossil resources, which would contribute towards a circular carbon economy (Bian et al., 2020).

Producing AA from CO_2 via MES (MES-AA) is yet far from economic viability. AA titer values have significantly increased in the last decade, but may now be plateauing far from the values expected for production of commodity chemicals (Prévoteau et al., 2020), although closer to those of food products (Bian et al., 2020). Multiple studies have discussed the need to focus on higher value chemicals such as caproate (Bian et al., 2020), which could potentially lead to achieving economic viability for MES (Jourdin et al., 2020). Regardless, the potential of producing MES-AA from CO_2 as a food is worth studying, because CO_2 utilization for the production of alternative foods for catastrophes has previously shown promise (García Martínez et al., 2021). A sustained increase in food prices due to a protracted global food shortage might make the economic case for MES-AA during a GCR scenario, even if it was not economically viable prior to the shortage.

This work aims to contribute to the novel research field of alternative foods for preventing malnutrition during potential global catastrophes to help reduce global catastrophic risk and existential risk. The scope is centered on estimating the cost and speed of producing food via MES, and comparing that to similar alternatives for similar catastrophic scenarios to help inform prioritization efforts.

2. Methods

Fig. 1 illustrates the proposed MES-AA production process and includes all major equipment except storage tanks. The liquid reaction medium contains electrolytes and nutrients, and is mixed with the CO_2 gaseous substrate and fixed at 30 °C prior to entry into the MES reactor. The reactor is a two-chambered, large-scale bioelectrochemical system that consists of an anode and a cathode compartment. The reactor lacks void space and has a 3:1 cathode-to-anode volume ratio, following the most promising experimental literature based on recent lab-scale research (Jourdin et al., 2018). The reactor also includes the electroactive inoculum (in the cathode compartment), electrodes, and membrane (cation exchange membrane (Jourdin et al., 2020),) needed for the MES reaction.

The overall reaction taking place in the two-chambered reactor is described by Equation (1) (Christodoulou et al., 2017). Water electrolysis occurs in the anode compartment due to the catalytic effect of the anode (a Pt/IrO_2-coated titanium electrode or other material). Water electrolysis releases protons, oxygen, and electrons. The protons pass through the cation exchange membrane from the anode to the cathode compartment. The electrons travel from the anode electrode to the cathode electrode through an external circuit. Finally, the electroactive bacteria culture present in the cathode compartment reduces the CO_2 to acetate using the hydrogen ions and electrons derived from the anode.

$$2CO_2 + 2H_2O \rightarrow CH_3COOH + 2O_2 \quad (1)$$

CO_2 can either be supplied from industrial sources or through direct

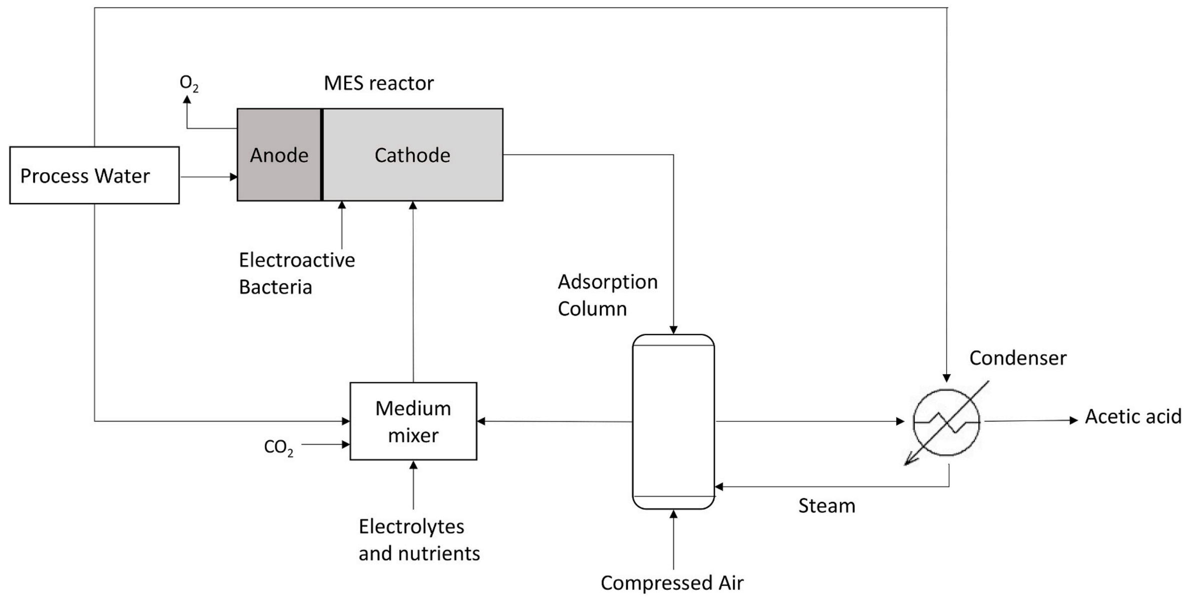

Fig. 1. Process diagram for MES-AA production. The two-chambered MES reactor has a 3:1 cathode-to-anode volume ratio.

air capture (DAC), and water is supplied as process water. The bioelectrochemical reaction is started by applying a specific potential (via electricity supplied by the grid) to achieve the preferred product. Several electrolytes and nutrients are also required to maintain the electroactive bacterial culture in the cathode compartment. AA is the main product of this reaction, as no other carboxylic acids are produced in significant quantities. O_2 is the only byproduct. The MES outlet is fed into a separation unit where the acetate is recovered and separated from any remaining biocatalysts, and the reactor solution is recycled back to the reactor. The O_2 byproduct from the anode compartment can be released into the atmosphere or stored for further use.

This analysis excluded separation, as scant work has been done on MES product separation, due to uncertainties around side reactions and final product requirements (Jourdin et al., 2020). Fig. 1 shows adsorption only as an example of a potentially viable separation method for AA.

2.1. Methodology overview

Two key metrics characterize the potential of an alternative food for GCRs: how quickly the production of the food could be scaled over time (as defined by the ramp-up speed), and how affordable the food would be during the catastrophe period (as defined by the retail price per calorie). It is also important to know if the most relevant input resources are present in sufficient quantities for global production ramp-up, in order to predict whether resource bottlenecks could arise. Fig. 2 presents the methodology used to estimate capital expenditure (CapEx), operational expenditure (OpEx), ramp-up speed, and retail cost. Each methodology is described in depth in the following sections.

There is significant uncertainty present in estimations of the CapEx and OpEx of a large-scale "n-th plant" MES-AA production plant, because currently there are no full-scale, commercial-size plants, as MES

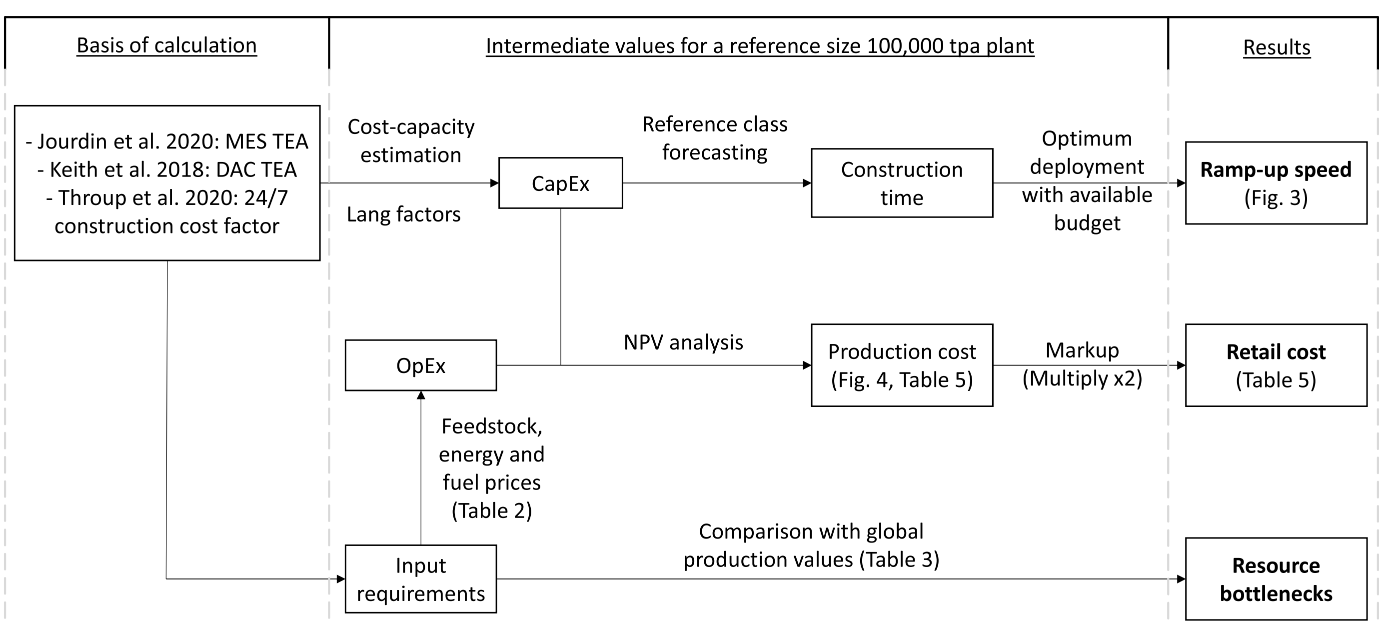

Fig. 2. *Methodology flowchart (TEA: techno-economic assessment, DAC: direct air capture of CO_2, CapEx: capital expenditure, OpEx: operational expenditure, NPV: net present value).*

exists only at the bench scale (Jourdin et al., 2020). A precise estimation of CapEx and OpEx would require performing design up to the FEL-3 (front-end loading) design stage, which is beyond the scope of this preliminary assessment. The current scope of this work resembles a FEL-2 design stage, in which the concept is defined and preliminary diagrams and budget estimates are produced, but the level of detail is not yet sufficient for construction (Warner, 2019).

The cost estimations used are from a published techno-economic assessment (TEA) of MES from CO_2 by (Jourdin et al., 2020). The CapEx and OpEx of obtaining the CO_2 feedstock are accounted for as a range of values to account for uncertainty. The low end of the range is based on free CO_2 and represents the option of leveraging existing carbon capture facilities (the capital and operational costs of these facilities are externalized). The high end of the range is based on the costs of constructing and operating DAC facilities.

2.2. CapEx estimation

The base case model estimate of the equipment capital cost obtained by (Jourdin et al., 2020) for MES from CO_2 is proposed here as representative of the future state of the technology. This equipment cost is \$6073/t (USD per tonne) for a reference production capacity of 2000 t/y. This estimate takes into account cathode, anode, membrane, current collector, reactor frame, and side equipment costs, but not separation equipment costs. Separation equipment has not been included in this analysis. Given the early stage of the MES technology, it is unclear which separation method would be used industrially. The estimate also includes side equipment (e.g., storage tanks, pumps, and heat exchangers), which was estimated at 10% of total CapEx. Preliminary estimations of capital costs for chemical plants are often obtained through a factored estimate of the equipment costs, using values traditionally known as Lang factors. A typical Lang factor for estimating the CapEx of industrial biotechnology processes is 3 times the equipment cost (Warner, 2019).

The cost-capacity estimation, or power-sizing scaling technique, is used to account for the reduction in cost at large-scale production plants. To determine the cost for the required large-scale plant size, the method is applied to the CapEx estimation as shown in Equation (2) (Sinnott, 2005). C_1 is the unit cost at capacity Q_1, C_2 is the unit cost at capacity Q_2, and x is the exponential scaling factor for cost capacity. A target production capacity of 100,000 t/y is chosen to harness economies of scale and to model a scenario where significant amounts of food could be quickly produced. This target production capacity also allows for a fair comparison with previously published research on industrial alternative foods for sun-blocking GCRs. The values used in the CapEx estimation are summarized in Table 1.

$$C_2 = C_1 (Q_2/Q_1)^x \tag{2}$$

Two distinct values of CapEx are estimated: one for the bare MES production plant and another for an MES plant coupled with infrastructure for DAC. The actual plant CapEx value is expected to fall within the range between these two values. The capital cost of DAC is estimated using the calcium looping process n-th plant estimate from (Keith et al., 2018) as a reference. The required CO_2 production capacity is estimated from Equation (1) with an overall CO_2 utilization of 95%, corresponding to a requirement of 1.54 kg CO_2/kg AA. Single-pass CO_2 conversion values close to 95% have been reported: 92.9% (Modestra and Mohan, 2019) and 94 ± 2% (Jourdin et al., 2015). These values could be improved even further if recycling unconverted CO_2.

A sun-blocking global catastrophe would abruptly inhibit conventional agriculture, making it essential to commence alternative food production early and to ramp up production quickly. Fast construction methods were reviewed, and nonstop construction (24/7) was found to be most promising. This method lowers total construction time to 32% of the original, but increases the capital cost by 47% (Throup et al., 2020), based on an analysis using the data and methods of (Hanna et al., 2007).

Table 1
Basis of calculation for the CapEx of the proposed MES-AA production plant.

Variable	Value	Unit	Reference
Reference MES plant equipment cost	6,073	\$/t/y AA	Jourdin et al. (2020)
Lang factor for MES	3	–	Warner (2019)
Reference MES plant capacity	2,000	t/y AA	Jourdin et al. (2020)
Target MES plant capacity	100,000	t/y AA	
Reference DAC plant capacity	980,000	t/y CO_2	Keith et al. (2018)
Reference DAC plant CapEx	935	x 10^6 \$	Keith et al. (2018)
Cost-capacity factor	0.6	–	Sinnott (2005)
CO_2 requirement	1.54	kg CO_2/kg AA	
24/7 construction factor	1.47	of CapEx	Throup et al. (2020)

2.3. Ramp-up speed estimation

The ramp-up speed is defined here as the increase in the amount of food that a given technology can produce, when as many new food production plants as possible are being continuously built over time. The ramp-up speed describes the proportion of global human caloric requirements that could be provided by an alternative food source, and how quickly. Production ramp-up speed is constrained by resource availability (both material and financial) for plant construction and operation. This limiting factor is roughly accounted for in this work by constraining available capital for nonstop MES production plant construction. The limit chosen is the capital expenditure, under normal conditions, of chemical industries as well as adjacent industries (e.g., power, pulp and paper, utilities, and beverages), which is estimated by (Damodaran, 2020) at \$489 x 10^9 per year. Given the unpredictability of sun-blocking GCRs, no time period is specified for the catastrophe conditions. Results can be considered to better represent the period of 2021–2026, given the use of the 2020 CapEx and population data as a basis. However, no significant changes to the estimated ramp-up speed are expected, because increases in global industrial production and population will likely balance each other out.

The time taken to construct a target-size production plant is obtained from the plant CapEx, via a logarithmic correlation based on (Martin et al., 2006). This correlation is used as a reference class forecasting method with the construction time of production plants as the reference class, meaning the construction time of future plants is estimated based on that of previously built plants. Next, an estimate is obtained for the number of target-size MES production plants that could be simultaneously constructed with the limited budget over a given time period. The ramp-up speed is then obtained as the rate at which useable food production capacity increases over time for the selected reference capacity. Using the data on world population and daily caloric requirement per person from Table 3, the result can be represented in terms of global human caloric requirements fulfilled over time, as shown in Fig. 3.

Each production plant is considered to have a startup period, during which average production capacity is one half of the installed capacity (Humbird et al., 2011); the startup period duration is considered to be one quarter of the plant's construction time at regular speed. An initial delay of 4 weeks is also incorporated into our ramp-up speed estimation, which is based on the time needed by complex industries to scale-up production during the COVID-19 pandemic (Betti and Heinzmann, 2020). Ramp-up speed estimation methodology is described more in depth in (Throup et al., 2020) and particularly in the supplementary material of (García Martínez et al., 2021).

2.4. Input analysis and OpEx estimation

The resource inputs and OpEx for a target-size plant are estimated from the model published by (Jourdin et al., 2020) for MES from CO_2,

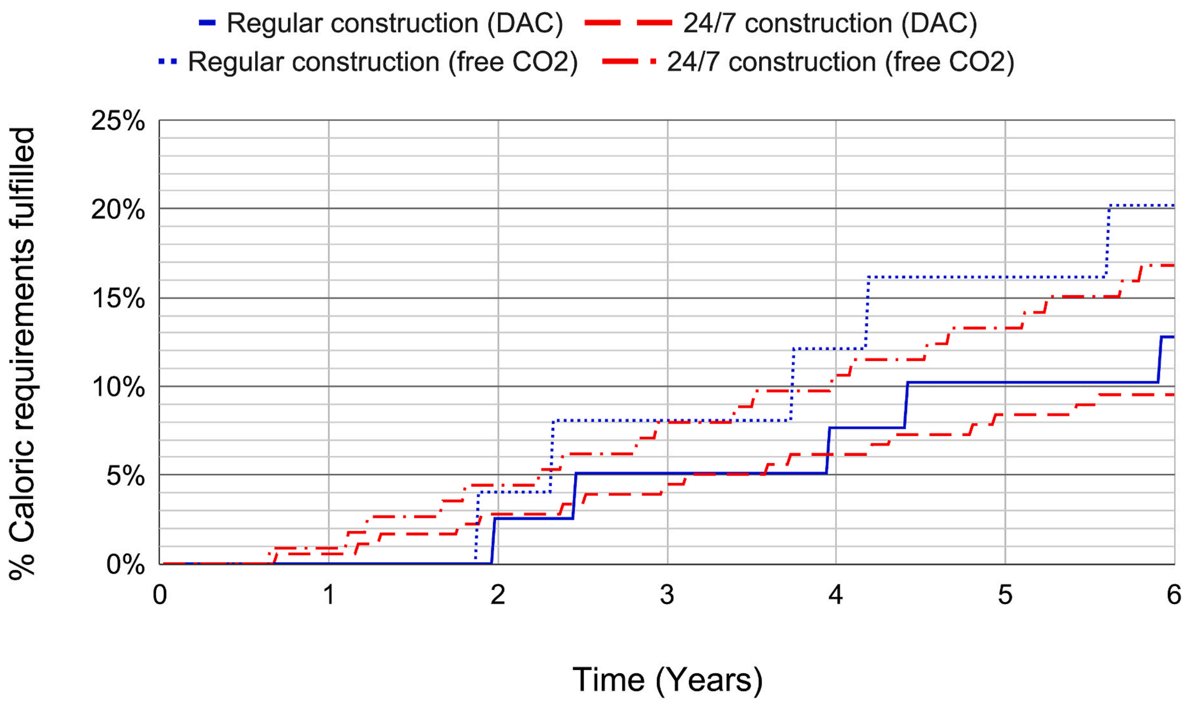

Fig. 3. Estimated ramp-up speeds of MES-AA production, expressed as a percentage of global human caloric requirements fulfilled. The results shown reflect the redirection of budgets away from similar industries towards MES-AA production, and show both regular and nonstop (24/7) construction speeds.

which includes electricity, pH control, nutrients, water, wastewater treatment, labor, maintenance, and other costs (see particularly the supplementary material of Jourdin et al., 2020). The study's base case values of these inputs per unit of AA were kept unchanged from the original model with the exception of electricity, because it is the major variable cost (40%–65% of the total). A range of reasonable electricity prices was used to account for uncertainty in market conditions and site location. A typical electricity cost for the aluminum industry was used for the low end of this range, and the current European industry average was used for the high end. A range of coulombic efficiencies represents the uncertainty in the efficiency when operating at a large scale, given that no real-world, industrial-scale examples of MES-AA production exist.

The other relevant input is the natural gas requirement for the DAC, which is only used for the high-end resource usage and cost. Natural gas consumption was estimated based on the reference DAC facility, which uses only natural gas as input (Keith et al., 2018). The low-end MES-AA OpEx is based on CO_2 being freely provided from an existing source, such as a storage facility or an industrial emitter with a carbon capture facility that accepts the operating costs of CO_2 capture as externalities. Any potential revenue from byproducts such as O_2 is not included. The values used in the OpEx estimation are summarized in Table 2.

Table 2
Basis of calculation for the proposed MES-AA production plant OpEx. *Low-end cost assumes free CO_2 supply.

Variable	Value		Unit	Reference
	Low-end cost	High-end cost		
Electricity price	0.03	0.13	$/kWh	Burns (2015) Eurostat (2019)
Coulombic efficiency	88	50	%	Jourdin et al. (2020)
Natural gas price	N.A.*	16.51	$/MWh	(Markets Insider, 2020)
DAC natural gas consumption	N.A.*	8.81	GJ NG/t CO_2	Keith et al. (2018)

A relevant input-related consideration is whether there would be sufficient resources to globally and quickly ramp up the production of MES-AA. To assess potential bottlenecks to fast ramp-up, the amount of resources required to fulfill the caloric requirements of the global population via MES-AA is estimated. The values used as a basis for this resource availability analysis are summarized in Table 3. The global human caloric requirements are estimated from the world population and the average daily caloric requirement per person. The equivalent amount of MES-AA needed to fulfill the requirements is then obtained from the caloric content of MES-AA. The resources required to produce this amount of MES-AA are quantified, including energy and material resources such as electricity and natural gas for DAC where applicable. Thermal energy requirements of the MES-AA production plant have not been estimated but could be significant depending on the separation process used, and are left for future research on the topic. Bacterial nutrients were accounted for as an operating cost, but are not included

Table 3
Basis of calculation for the resource availability analysis. *No matter how dire the food crisis is, the presence of some amount of food waste throughout the system is unavoidable. In the proposed scenario, food waste is expected to be lower than the current value due to decreased food availability. Additionally, the MES-AA has an indefinite shelf life, so a reasonably low value of 12% food waste was considered (Denkenberger and Pearce, 2014).

Variable	Value	Unit	Reference
World population	7.8	x 10^9 people	Worldometers (2020)
Expected food waste	12	% of calories produced	*
Average daily caloric requirement per person	2,100	kcal/person/day	World Health Organization (2004)
Calorie content of acetic acid	3.49	kcal/g	Greenfield and Southgate (2003)
Global average electricity consumption	2,551	GW	Sönnichsen (2020)
Global electricity capacity	5,150	GW	Sönnichsen (2019)
Global natural gas production	4,198	x 10^9 m^3/y	IEA (2019)
Energy content of natural gas	39.1	MJ/m^3	Engineering ToolBox (2005)

in this bottleneck analysis.

2.5. Economic analysis

The break-even cost of the MES-AA food product was estimated for regular conditions and catastrophe conditions by performing net present value (NPV) analyses. For both analyses, the break-even production cost was determined by calculating the required revenue per unit of MES-AA produced when NPV equals zero. The analysis of regular conditions, done for comparison, used a typical plant lifetime of twenty years and regular construction costs. Several estimates were adjusted for the NPV analysis representative of conditions during a sun-blocking GCR scenario. For this calculation, the increased capital cost of 24/7 construction applies. A six-year operation period was used, which is shorter than a normal chemical plant operation timeline but is representative of a strong food shock's duration. All production equipment was considered to be depreciated after this six-year period. This is likely conservative, given that some lower-priced food products could continue to be sold after this period, some production equipment would have salvage value, or the production infrastructure could be built with less-expensive materials in response to the short operation period. Given the absence of statistical data for the technology, a 10% discount rate was used to represent the time value of money (Short et al., 1995). Working capital was estimated as 10% of the CapEx value. Financing for the project comprised 70% equity (with a 10% return on investment), and 30% loaned capital with an 8% annual interest rate and a 10-year repayment period, while revenue was considered to be subject to a 35% tax rate (Humbird et al., 2011).

3. Results

3.1. CapEx and OpEx of reference plant

The capital cost of CO_2 capture is estimated between zero, which represents the case of a CO_2 capture facility already in place, and $257 million which represents construction of a new DAC facility. The capital cost of an MES production plant with target production capacity (i.e., 100,000 t/y) is $381 million. This results in a total CapEx estimate of $381–$638 million, or $556–$932 million when using 24/7 construction. These CapEx estimates translate into an investment per unit of installed capacity of approximately $3,800–$6,400/t/y AA, or $5,600–$9,300/t/y AA when using 24/7 construction. The estimated OpEx ranges between $1,100–$4,000/t AA.

3.2. Ramp-up speed and potential bottlenecks

The construction time for a target size plant is estimated at 30–32 weeks when using 24/7 construction. Fig. 3 shows MES-AA ramp-up speeds for the scenario in which the global budget for chemical and related industries can be effectively redirected to fast construction of production plants. The results are given for the case of using CO_2 from existing capture facilities and for the case of building DAC facilities to obtain the CO_2. Based on the current state of MES technology, less than 1% of global human caloric requirements could be fulfilled at the end of the first year after the catastrophic event.

Nearly 2 x 10^9 t/y of AA would be required to fulfill global human caloric requirements. The amount of input resources required to fulfill these caloric requirements via MES-AA from CO_2 are shown in Table 4. Electricity consumption of MES is high, which could be a bottleneck to production ramp up. However, given that MES-AA production is expected to reach at most a production level equivalent to 20% of global human caloric requirements in the 6th year after the catastrophe, its energy requirements are not expected to surpass 40% of current global electricity consumption.

Table 4
Low end and high end estimates of proportions of global resources required to fulfill global human caloric requirements via MES-AA, while accounting for 12% food waste. Note that the high end values include DAC as a CO_2 source.

	Low end	High end
Electricity requirement of MES (MWh/t product)	12.3	21.7
Energy efficiency: electricity to calories	33%	19%
Proportion of global natural gas production	N.A.	16%
Proportion of global electricity consumption	108%	189%
Proportion of global electricity capacity	53%	94%

3.3. Food price

Results of the NPV analyses performed (as described in Section 2.5 for MES-AA price) are shown in Fig. 4. The "Catastrophe" and "Regular conditions" labels represent different economic premises for each numerical analysis. The cost breakdowns labelled "Catastrophe" represent the proposed catastrophe scenario (i.e., a plant operation lifetime of six years and the increased costs of 24/7 construction). The cost breakdowns labelled "Regular conditions," made for comparison, represent the NPV analysis where typical economic conditions are represented with a twenty-year plant operation lifetime and regular construction costs. For each NPV analysis the product cost was calculated for both a low price bound (based on low CapEx and OpEx, see Fig. 4a) and a high price bound (based on high CapEx and OpEx, i.e., including DAC capital and the high end of electricity consumption and price estimates, see Fig. 4b).

For each scenario, the retail cost of the MES-AA product was determined by adding a 100% markup to the wholesale production cost that is shown in Fig. 4 (McCray, 2010). The retail cost accounts for additional costs including distribution and others. This retail cost is considered distinct from a retail price, because uncertain market conditions during a global catastrophe could alter the sales price. Resulting retail costs are shown in Table 5. Because the same 100% markup value was used to determine each retail cost, the difference between the break-even cost and the retail cost can vary considerably for different scenarios. Overall, the retail cost for fulfilling a person's daily caloric requirements with the MES-AA product would amount to approximately $4 to $9 per day.

4. Discussion

Infrastructure and industrial capabilities of most world regions are considered to remain largely functional in the proposed sun-blocking GCR scenario. This would allow for the construction and continued operation of chemical and biochemical production plants such as the MES-AA food production concept described here. This consideration is expected even in the most dire sun-blocking GCR scenario (i.e., nuclear winter), for regions which would not have been targeted by nuclear attacks. If instead significant loss of global industry were to occur simultaneously, different food solutions would be required, such as those described in (Denkenberger et al., 2017).

There are numerous advantages to using MES as an alternative food production method during a global catastrophe: (a) it requires neither arable land nor sunlight, (b) it does not require the addition of high nutrient quantities or high-quality water, (c) it does not release pollutants in the ecosystem, offering a sustainable and eco-friendly process, (d) it uses CO_2 that is abundant in the atmosphere or that can be sourced directly from CO_2-producing facilities at minimal costs, (e) it can use biocatalysts instead of chemical/metal catalysts (Nevin et al., 2010) and (f) the MES-AA product has an indefinite shelf life, similar to vinegar that is safe for use long after its expiration date.

Even though the use of CO_2 as an input implies reduced feedstock costs, it introduces two significant input resource bottlenecks to fast ramp-up of MES-AA. Due to the high thermodynamic stability of CO_2 (Bian et al., 2020), large amounts of energy are required to break the

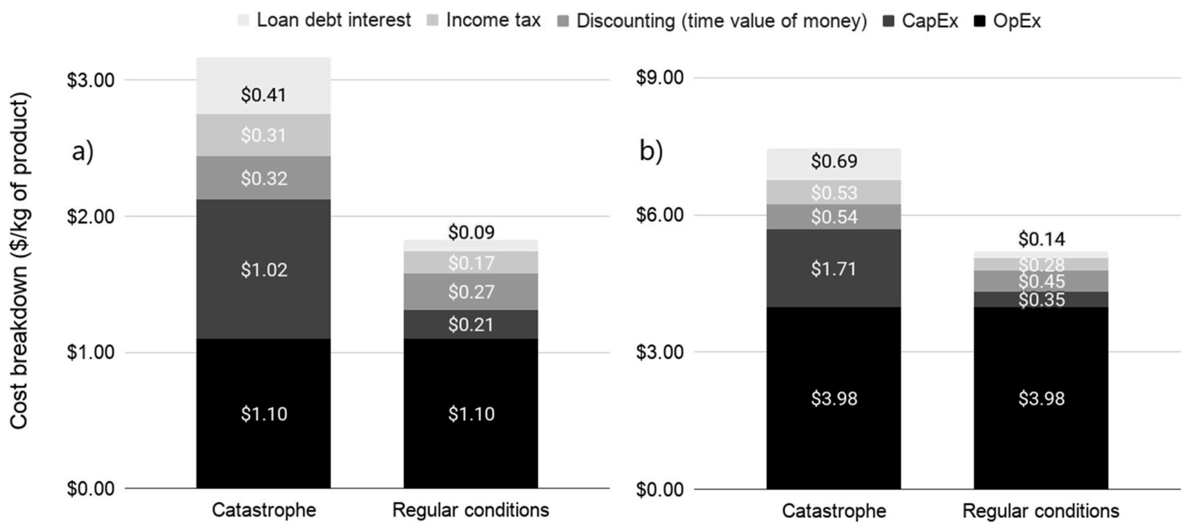

Fig. 4. Breakdown of the contributions to the wholesale production cost incurred per unit (kg dry) of MES-AA produced for different scenarios. The low end of manufacturing cost is shown on the left (4a), the high end on the right (4b).

Table 5
Retail cost of MES-AA product, in $/kg (dry), for different cost scenarios.

Scenario:	Catastrophe conditions (6 years plant lifetime, 24/7 construction)		Regular conditions (20 years plant lifetime, regular construction)	
Energy and feedstock cost	Free CO_2, low electricity cost	DAC, high electricity cost	Free CO_2, low electricity cost	DAC, high electricity cost
Wholesale cost ($/kg, dry)	$3.17	$7.45	$1.83	$5.20
Retail cost ($/kg, dry)	$6.34	$14.90	$3.66	$10.40

double bonds and allow for synthesis of longer chain molecules. An electricity supply bottleneck could arise when ramping up production, because fulfilling global human caloric requirements with MES-AA would require the equivalent of over 100% of current global electricity consumption (see Table 4). MES uses biocatalysts (Das et al., 2020) instead of metal catalysts, and although biocatalysts can reduce the operational and capital costs of the MES process because they don't require regular maintenance or replacement, the energy requirements and therefore electricity costs remain high. However, in terms of efficiency, the calorie return per unit of electricity invested in MES-AA is expected to be somewhat better than that of single cell protein produced from hydrogen oxidizing bacteria (García Martínez et al., 2021), and considerably better than microalgae (Alvarado et al., 2021) or vegetables (Denkenberger et al., 2019) grown with artificial light.

Using waste CO_2 produced from other industries comes with its own disadvantages. The CO_2 is commonly part of a flue gas stream containing toxic compounds (i.e., hydrogen sulfide and nitrogen oxides) that require gas cleaning. This CO_2 also comes with a high temperature that could harm the microbial environment and thus would decrease the efficiency of the system (ElMekawy et al., 2016), requiring cooling. Nonetheless, CO_2 capture from industrial sources is expected to be the cheapest widely available source. Fulfilling global human caloric requirements via MES would require over 3 x 10^9 tonnes of CO_2, which large industrial point sources may not necessarily be able to supply in a catastrophic situation, creating a feedstock bottleneck for MES. However, DAC can be used to overcome this potential bottleneck, because it can be used to obtain CO_2 anywhere, regardless of availability of industrial emissions. For this reason, we presented two scenarios: an optimistic one in which the cost of CO_2 capture is externalized to industrial partners, and a pessimistic one in which CO_2 is extracted from the atmosphere, incurring a larger expenditure (see Fig. 3).

CapEx of MES product separation is not included in this analysis, while the OpEx is roughly estimated from (Jourdin et al., 2020), but separation costs are worth discussing in more depth. In this work, AA and water are the only products accounted for in the MES reactor, due to the use of an acetogenic-rich bacteria culture. However, the effluent would likely contain a mixture of various products (depending on the source of the bacterial community) which may require further separation, adding to the production cost (Gildemyn et al., 2015). Little work has been done on MES product separation due to uncertainties around MES side reactions and final product requirements. However, adsorption was explored as a potential separation method to provide a preliminary assessment in recovering edible acetate (see Fig. 1). Adsorption allows for a high recovery (75%) of low-concentration acetate (<5% wt). A patent suggests these titre yields can be concentrated up to 20% wt via adsorption using a macroporous resin, such as D301G (王屹翀, 2015) followed by steam desorption. This solution could be sold to consumers to enable home dilution of acetate for consumption. Further work is needed to validate adsorption as a viable MES separation method, but this analysis provides an apparently feasible basis for recovering AA from MES systems.

There is considerable uncertainty in the expected retail cost of MES-AA as alternative food for sun-blocking global catastrophes, with the electricity cost being the major variable. At the expected price range calculated for MES-AA, based on current global income levels, between 40% and 70% of the global population could afford sufficient amounts of the MES-AA product to meet their total caloric needs (Denkenberger et al., 2019). Of note is that the financial assumptions in this work are representative of non-catastrophic conditions (i.e., business as usual), but a global, sun-blocking catastrophe would likely catalyze financial realities that would be complex and likely unpredictable, and that are beyond the scope of this work. Relatedly, the market price of the inputs needed to produce MES-AA may be affected as its production is significantly scaled up. Although additional research on market equilibrium during a global food-related catastrophe may enable more precise estimates of alternative food prices, the construction budget is not expected to be a constraint, given the several trillions of government expenditure towards economic stimulus in response to the COVID-19 pandemic (Andrijevic et al., 2020), a scenario far less severe than a sun-blocking catastrophe.

An alternative food for GCRs needs to perform in two different metrics: ramp-up speed and retail cost in catastrophe conditions.

Because AA does not fulfill special nutritional requirements, unlike single cell protein (García Martínez et al, 2020, 2021) or synthetic fat, it needs to outperform the next-best industrial food alternatives either in terms of cost per calorie or ramp-up speed. Otherwise, the other alternative foods would be a better allocation of industrial resources in the catastrophe scenario. It is important to note, however, that non-industrial or low-tech alternative food sources such as seaweed cultivation or low-tech greenhouses (Alvarado et al., 2020), if feasible, would likely scale faster and be cheaper than the industrial options.

Lignocellulosic sugar (Throup et al., 2020) is currently expected to be the lowest-priced industrial alternative food for GCRs. It would cost approximately $2 to fulfill a person's daily caloric requirements with lignocellulosic sugar, in comparison to $4–$9 for MES-AA. Similarly, to compete in speed, MES-AA would have to ramp up at least at fast as the best industrial food alternative, which in this case is single cell protein from methane (García Martínez et al., 2020). Using the capital cost as a proxy of ramp-up speed, MES-AA would have to cost at most $4,200/t/y, compared to the expected average cost of $7,400/t/y. With the current state of the MES technology, significant cost reductions are needed for MES to bridge these gaps. Costs related to separation equipment and thermal energy usage have not been included in this analysis, but accounting for them would only strengthen the conclusion that MES is still far from being competitive as an alternative food production method.

Key MES performance parameters have considerably increased in the last years but seem to be plateauing at lower values than would allow competitiveness for production of commodity chemicals (Prévoteau et al., 2020). However, fundamental scientific research into MES continues, and possible improvements have been suggested, including the use of media with high ionic strength to reduce internal resistance (Prévoteau et al., 2020) and genetic engineering (Glaven, 2019). If longer chain fatty acids with 8 or more carbon atoms could be efficiently synthesized via MES in the future, the potential of MES as an alternative food production method for GCRs could be increased significantly, due to the nutritional importance of lipids. Additionally, coupling of MES with other technologies could also decrease costs and improve the economic feasibility of such biotechnology in small-scale productions (Christodoulou et al., 2017). The next decades of fundamental and applied research will uncover the capabilities of MES, and while it is not recommended for production of alternative foods for GCRs now, this may change.

Eventually MES may become economically viable for production of commodity chemicals such as AA or longer chain fatty acids during business as usual conditions, which would be quite beneficial in case of a sun-blocking GCR. The factories could be repurposed for food production, which would be much faster than construction of new facilities. For example, if in the future MES were to take over the entire global AA market of 16 Mt/y (Christodoulou et al., 2017), that could imply a head start equivalent to nearly 1% of the global human caloric requirements. However, this is an even more ambitious goal than the one proposed in this work, given the lower market price of commodity chemicals (currently $0.4–$0.8/kg bulk for AA) compared to the prices of industrial alternative foods for GCRs.

However, even if MES becomes competitive as an alternative food for GCRs in terms of cost and/or ramp-up speed, there would still remain a significant bottleneck to ramp-up: the availability of noble metals such as platinum. Although widely available and cheap cathode materials such as carbon felt have shown satisfactory MES performance (Jourdin et al., 2018, 2020), the current industry standard anode catalyst material is platinum. As an example, the electrodes of a standard polymer electrolyte membrane (PEM) electrolysis unit contain approximately $8 worth of material per kW of installed capacity, with this material cost being dominated by the cost of platinum (James et al., 2018). At a price of $1500 per troy ounce (James et al., 2018), assuming the same platinum usage for MES would translate to a requirement of over 300,000 t of platinum to fulfill global human caloric requirements using MES. This requirement far surpasses both global platinum reserves, estimated at 69,000 t (Garside, 2020a), and annual platinum production, approximately 200 t (Garside, 2020b). Despite significant research efforts to reduce reliance on the use of noble metals in electrodes, there are currently few viable alternative materials available (Sun et al., 2018). This bottleneck could potentially be mitigated by replacing the typical double-chamber reactor design with a single-chamber cathodic reactor design, to which the protons would be supplied in the form of molecular hydrogen, which could be obtained via water electrolysis, or from coal or biomass gasification. A single-chamber design would also have the advantage of reducing the electricity consumption of the process, as part of the energy requirement would be fulfilled by the fuel instead of the electrical grid. This would however be a trade-off situation, as the capital intensity of gasification facilities would considerably increase capital cost. A comparable production system with a similar trade-off situation is found in hydrogen-based single cell protein production (García Martínez et al., 2021). Alternatively, the development of an efficient MES reactor with bioanode could eliminate the use of platinum. However, such systems are currently operating with lower efficiency, resulting in higher costs (Jourdin et al., 2020). Reactor design is a complex topic and further work is required for large scale MES production.

Related applications for MES as a food production method (at a small scale) include refuges underground, underwater, or in space. Surface-independent refuges could strengthen the potential for human survival and humanity's ability to rebuild civilization after a global catastrophe (Baum et al., 2015). The food-production and life-support systems used in refuges could resemble those used on space missions (e.g., to the International Space Station, the Moon, or Mars), for which MES could also be a viable food production method (Alvarado et al., 2021, Alvarado et al. to be published). Further cost reductions of MES technology may enable its use as a sustainable food production method during business-as-usual conditions, given its CO_2 utilization potential and its lower land and water usage compared to conventional agricultural AA production.

Finally, there remains the question of edibility and palatability of the MES products. Food safety studies would be necessary prior to rolling out MES products for human consumption, whether in a catastrophic scenario or not. Additional purification and quality control processes not discussed here may be required. Once safety is established, research into how the calories contained in the product could be made into a more palatable form may be useful, since many people may not find drinking vinegar to be a pleasing prospect.

5. Conclusions

The potential of MES as an alternative food production method for GCRs has been presented. The CapEx for a MES-AA production facility was estimated at $5,600–$9,300/t/y when built using 24/7 construction to quickly produce MES-AA during a food-related global catastrophe, with the CapEx depending on the availability of CO_2 production facilities. The expected retail cost of the product was estimated at $6–$15/kg (dry), depending mostly on the cost of electricity and energy efficiency.

The production ramp-up of MES-AA could be significantly affected by potential bottlenecks, such as high electricity usage and limited availability of noble metals for anode construction. A possible solution has been proposed, based on feeding gasification-based hydrogen to a single-chamber cathodic MES reactor.

MES-AA is currently not recommended as an alternative food for global catastrophes that would inhibit conventional agriculture, due to the high production cost and capital intensity of this product. In such a scenario, it would be preferable to direct industrial resources towards the production of other industrial alternative foods, such as lignocellulosic sugar or single cell protein from methane, because of their superior cost effectiveness and/or ramp-up speed. However, improvements to MES technology through research in the coming decades could potentially make it competitive as an industrial alternative food production method.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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