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Perspective

Electro-agriculture: Revolutionizing farming for a sustainable future

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SUMMARY

For millennia, humanity has depended on photosynthesis to cultivate crops and feed a growing population. However, the escalating challenges of climate change and global hunger now compel us to surpass the efficiency limitations of photosynthesis. Here, we propose the adoption of an electro-agriculture (electro-ag) framework that combines CO_2 electrolysis with biological systems to enhance food production efficiency. Adopting a food system based entirely on electro-ag could reduce United States agricultural land use by 88%, freeing nearly half of the country's land for ecosystem restoration and natural carbon sequestration. Electro-ag bypasses traditional photosynthesis, enabling food cultivation in non-arable urban centers, arid deserts, and even outer space environments. We offer a new strategy that improves energy efficiency by an order of magnitude compared with photosynthesis, along with essential guidance for developing electro-ag focused on staple crops, to maximize benefits for regions facing food insecurity. This innovative approach to agriculture holds significant promise in reducing environmental impacts, streamlining supply chains, and addressing the global food crisis.

CONTEXT & SCALE

The demand for food production is intensifying with a rapidly growing population, yet farmers around the world face unprecedented challenges owing to shifting climatic conditions. Controlled environment and vertical farming have emerged as a potential solution to boost resource use efficiency and food output per unit of land while allowing for cultivation in urban and arid regions, but widespread adoption has been hindered by substantial energy requirements. Recent developments in CO_2/CO electrolysis as well as advances in genetic engineering and selective breeding have laid the groundwork for the emergence of electro-ag to substantially reduce the energy needs of vertical farming. Fueled by acetate derived from CO_2 using renewable electricity, electro-ag enables the heterotrophic growth of food crops. Unlike traditional controlled environments or conventional farming, electro-ag is not constrained by the same efficiency limitations of photosynthesis. Instead, the efficient metabolic pathways of acetate utilization are harnessed to allow for at least a 4-fold improvement in solar-to-food efficiency, with future efforts potentially leading to an order of magnitude improvement in energy solar-to-food efficiency. If the United States food supply was

INTRODUCTION

Today, food production makes up a third of global anthropogenic greenhouse gas emissions, with nearly half of the world's habitable land being used for agricultural purposes.[1,2] As the global population continues to surge and developing nations adopt Western dietary patterns, the environmental impact of food production is only expected to grow. Given agriculture is one of the most difficult sectors to decarbonize, this is a major challenge for achieving net zero emissions by 2050 as outlined in the Paris Agreement.[3] Consequently, there is an urgent need for the global food system to be reimagined to sustain a habitable planet. While considerable attention has been focused on vertical farming, these systems are traditionally beset by the need for massive amounts of energy for artificial lighting, which hinders practicality. However, recent advances in breeding and genetic engineering coupled with improvements in CO_2 electrolysis have heralded the emergence of a groundbreaking revolution in farming: electro-agriculture (electro-ag). Unlike traditional food crop production strategies that rely on photosynthesis, electro-ag can enable the cultivation of food in the absence of light.

Electro-ag uses renewable energy to power the electrochemical transformation of CO_2 into reduced carbon compounds that can then be used to cultivate food-producing organisms. The production of food with electro-ag takes place in a controlled environment, but unlike current systems, large banks of lights and HVAC cooling systems to dissipate their heat are not required. 30%–50% of the electricity supplied to

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the LED grow lights in conventional vertical farming is lost to heat, which requires substantial cooling costs for these systems.[4,5] These grow lights are unnecessary for electro-ag, which enables food production in darkness. In electro-ag, electrolyzer effluent is delivered to the food-producing organisms using hydroponic systems, reducing water use by 95% compared with conventional agriculture.[6] This system eliminates the need for pesticides and also utilizes fertilizer much more efficiently. Globally, 50%–60% of applied fertilizer leaks into the environment during conventional agriculture practices, leading to increased greenhouse gas emissions and eutrophication of waterways.[7,8] Producing synthetic nitrogen fertilizers via the Haber Bosch process accounts for about 2% of global CO_2 emissions, highlighting the need for more efficient use of this fixed nitrogen.[9,10] The synthetic ammonia produced via Haber Bosch can then be neutralized with nitric acid to produce ammonium nitrate fertilizer. In the closed, recirculated electro-ag system, the ammonium nitrate and ammonia fertilizer cannot escape into the environment, resulting in higher nitrogen use efficiency and reducing environmental eutrophication by 70%–90%.[10] Further environmental benefits can be gained by electrifying fertilizer production with green hydrogen, which could decrease greenhouse gas emissions from ammonia production by >90%.[11]

Much recent work has sought to push electro-ag technology toward commercialization. In 2022, an electro-ag proof-of-concept system demonstrated a 4-fold improvement in energy efficiency over photosynthesis.[12] Additionally, an electro-ag system designed by team "NOLUX" (Latin for no light) won phases 1 and 2 of the NASA Deep Space Food Challenge.[13,14] In phase 3, an electro-ag prototype capable of supporting a 4-astronaut crew on a simulated space mission was validated by NASA and placed among the top 3 technologies.[15] Additionally, the Bill & Melinda Gates Foundation has partnered with the Novo Nordisk Foundation to fund a $28 million Acetate Consortium to accelerate the commercialization of electro-ag toward edible protein while generating interest from vertical farming company, Square Roots, to pursue electro-ag toward plant crops.[16,17] Electro-ag technology has also attracted the interest of the US Defense Advanced Research Project Agency's Cornucopia program, which is seeking to generate food from air, water, and electricity on the back of Humvees to streamline military resupply chains.[18]

Electro-ag revolutionizes food production by decoupling it from natural environmental constraints. Growing food with electro-ag in a controlled environment offers the ability to produce food year-round, anywhere in the world. It enables the cultivation of fresh food in urban food deserts, significantly improving food security in densely populated areas. Electro-ag also bolsters agricultural productivity in regions with extreme climates, such as sub-Saharan Africa or Northern Canada, where traditional farming methods face significant challenges. Electro-ag systems are ideal for deployment following natural disasters, providing a reliable source of food when traditional supply chains are disrupted. Furthermore, electro-ag can maintain stable crop production in scenarios where solar photons are limited, such as during solar geoengineering or nuclear winter events. However, it should be noted that in the scenario where access to solar photons is impeded, other sources of electricity than solar photovoltaics should be considered. Electro-ag can also produce food in entirely built environments, like a spacecraft. By transforming water and waste CO_2 into essential food and oxygen, electro-ag can support astronauts on deep space missions and facilitate extraterrestrial colonization. In this perspective, we explore the numerous benefits of electro-ag and outline pathways for enhancing this technology. By focusing on

produced via electro-ag, land usage could be decreased by 88% while substantially streamlining food supply chains by decentralizing food production.

There are many advantages of an electro-ag-based global food system. By improving efficiency and decreasing land usage, a large portion of Earth's land could be rewilded to restore ecosystems supporting natural carbon sequestration. Additionally, electro-ag systems can be deployed in extreme environments such as deserts, cities, or even on Mars where it is otherwise difficult to grow food. Electro-ag can also help avoid devastating food price spikes by reducing the impact of extreme weather and localizing food production. Electro-ag is poised to revolutionize the realm of food production by offering a sustainable pathway toward a more resilient and equitable food system. Future efforts should seek to further improve the energy efficiency of electro-ag while working toward the production of calorie-dense staple crops to help combat global hunger.

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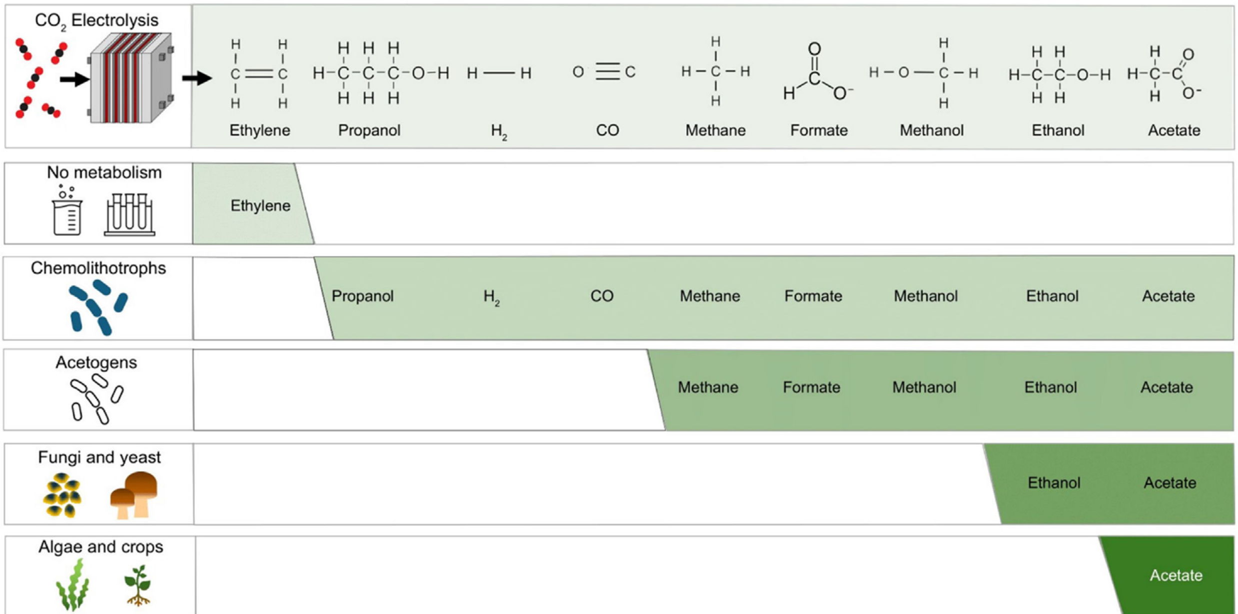

Electrochemical	Ethylene	Propanol	H_2	CO	Methane	Formate	Methanol	Ethanol	Acetate
Pathway of metabolism	-	Methylcitrate cycle	CBB cycle	W-L pathway	RuMP cycle	rGly pathway	RuMP cycle	Ethanol assimilation	Acetate assimilation
$\Delta H_c°$ (kJ/mol)	-1411	-2021	-285	-283	-890	-254	-726	-1367	-875
Steps to generate one acetyl-CoA	-	6	20	8	18	14	19	3	1
Solubility in water at 25°C, 1 atm (mol/L)	-	Miscible	7.79×10^4	0.034	2.42×10^4	Miscible	Miscible	Miscible	Miscible
e^{-1} transfered to e^{-1} carriers (NADH, $FADH_2$)	-	10	2	1	6	2	6	12	8

Figure 1. Metabolic compatibility of CO_2 electrolysis products with biological organisms

This table indicates the chemical properties of different electrochemical products such as their established biological metabolic pathway, enthalpy of combustion at standard conditions ($\Delta H_c°$), enzymatic steps required for conversion to the central bioenergy metabolite acetyl-CoA, solubility, and the number of electrons transferred to electron carriers during metabolism.

*Calvin-Benson-Bassham (CBB), Wood-Ljungdahl (W-L), ribulose monophosphate (RuMP), reductive glycine (rGly), nicotinamide adenine dinucleotide (NADH), and flavin adenine dinucleotide ($FADH_2$).

sustainability and adaptability, electro-ag holds the promise of revolutionizing food production in both remote and challenging environments, ensuring a resilient and secure global food system.

ELECTRO-AGRICULTURE SYSTEM DESIGN AND RATIONALE

A variety of single-carbon and multi-carbon chemicals can be electrochemically synthesized from CO_2. Many of these chemicals, however, are not biologically compatible, inefficient for supporting growth, or involve metabolic pathways that are complex to engineer into new organisms (Figure 1). For example, CO_2 electrolysis has achieved relatively high selectivity toward ethylene,[19] yet no known biological mechanisms allow organisms to utilize it as an energy or carbon source. CO and H_2, both highly efficient outputs of electrochemical processes, can be utilized by chemolithotrophs like *Cupriavidus necator*. These extremophile bacteria, however, are limited to producing raw proteins or biochemicals.[20–22] Both CO and H_2 also face challenges such as poor solubility in water, requiring pressurization to enhance their transfer to aqueous bacterial cultures.[23] Other products of CO_2 electrolysis, such as formate, methanol, and methane, are metabolizable by acetogen bacteria. Like CO and H_2, gaseous methane has poor solubility in aqueous solutions, which hampers its mass transfer to microorganisms that can metabolically convert it to methanol and consume it through the same metabolic pathway as methanol. The metabolism of methanol involves the formation of the highly toxic intermediate, formaldehyde, which severely restricts metabolic efficiency, slows growth, and can cause cell death if it accumulates. Formate is also toxic to microbes and can result in a long lag phase before growth occurs.[24] The consumption of formate by acetogens also occurs at limited growth rates, restricting its broader application in chemical and food production. Although there has been significant advancement in the electrochemical production of propanol,[25,26] another potential chemolithotrophic substrate, it is still relatively challenging to achieve high Faradaic efficiency and current density toward propanol through CO_2/CO electrolysis. While chemicals such as CO, H_2, formate, methanol, and methane can be metabolized by bacteria, these organisms are not currently consumed as food, limiting the practical application of these electrochemical products in food production.

The most readily consumable carbon sources produced via CO_2 electrolysis at relatively high efficiencies are ethanol and acetate.[27–29] Metabolically, ethanol is converted to acetate with alcohol dehydrogenase and acetaldehyde dehydrogenase. Both ethanol and acetate can be used to cultivate common eukaryotic organisms such as yeast or mushroom-producing fungi, which are already consumed as food (Figure 1). Acetate can also serve as the sole carbon and energy source for some species of green algae. Acetate is highly miscible in water and has a one-step metabolic route to acetyl coenzyme A (acetyl-CoA), the biologically active form of acetate that is a substrate in many biochemical reactions. The high miscibility and accessibility to acetyl-CoA makes acetate consumption easy to engineer, allowing acetate to be readily metabolized and used for energy and biomass production (Figure 1). Acetate can also be taken up and metabolized by plants; recently, electrochemically produced acetate has been shown to be able to support the production of crops with a 4x improvement in solar-to-food efficiency over conventional photosynthetic agricultural approaches.[12] The high concentration, efficiency, and purity of electrochemically produced acetate,[29] its short metabolic pathway, relatively high number of donor electrons, and compatibility with many organisms already cultivated for food make acetate the leading CO_2 electrolysis product for electro-ag feedstock.

Most food consumed by humans originates from plants, making it essential for electro-ag systems to produce crop plants effectively. All adult crop plants are photoautotrophic, relying on photosynthesis to build biomass. In an electro-ag system, however, plants must be heterotrophic, consuming acetate to construct biomass. Adult plant metabolism is not optimized for heterotrophic growth on acetate. Acetate is converted to acetyl-CoA, which enters the citric acid (TCA) cycle to fuel cellular energy production. Each two-carbon acetyl-CoA fed into the TCA cycle results in the release of two molecules of CO_2, resulting in a zero net gain of carbon atoms, making acetate-fueled growth through the TCA cycle inefficient for building biomass (Figure 2A). Fortunately, plants possess natural metabolic pathways to bypass this carbon loss. Unlike adult plants that rely on photosynthesis, germinating seeds depend on heterotrophic growth, using stored sugars and lipids to build new biomass. These lipids are broken down into acetyl-CoA, which enters the glyoxylate cycle instead of the TCA cycle. The glyoxylate cycle bypasses the two decarboxylation steps of the TCA cycle through the action of two key enzymes, isocitrate lyase and malate synthase (Figure 2A).[30] This allows the stored carbon in seed lipids to be converted into plant biomass. However, this metabolic cycle becomes dormant in adult plants

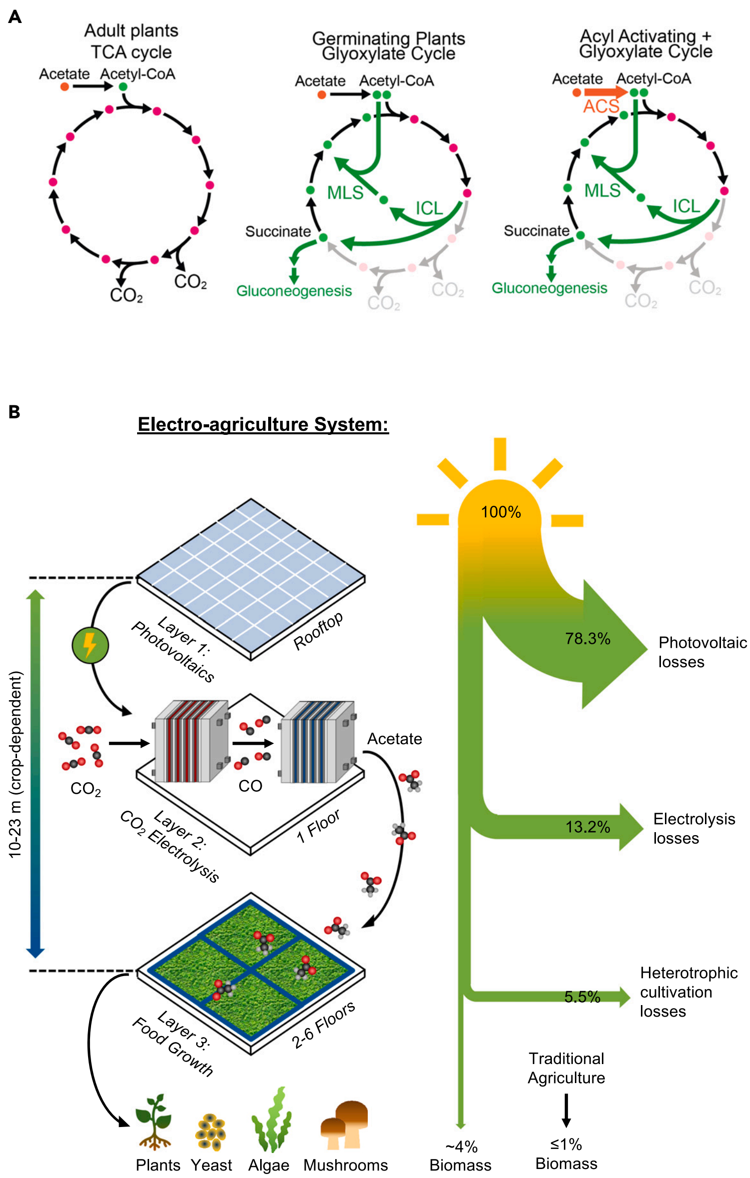

Figure 2. Enabling efficient crop growth with CO_2 electrolysis

(A) Metabolic pathways for food production.

(B) Vertical electro-ag system schematic and energy efficiency.

once photosynthesis begins. Genetic engineering approaches can be taken to enhance plant acetate metabolism.[31] In other organisms, acetate utilization has been improved by overexpressing enzymes that convert acetate into acetyl-CoA (Figure 2A).[32] By reactivating the dormant glyoxylate cycle and increasing the conversion of acetate to acetyl-CoA, adult plants can use electrochemically derived acetate to generate energy and build biomass, providing an alternative to photosynthetic carbon fixation.

Engineering plants to be able to grow on acetate is a critical step in enabling electro-ag, but the combined system is composed of three steps. These three steps can be vertically integrated in layers to minimize land usage (Figure 2B). The first layer is the

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roof of the vertical electro-ag system, which is covered in solar photovoltaics to provide affordable green electrons to power the electrolysis system. Layer two comprises a tandem CO_2 electrolysis system that will convert captured CO_2 into acetate at ambient conditions. The tandem CO_2 electrolysis system is composed of two electrolyzers: the first electrolyzer produces CO from CO_2, while the second downstream electrolyzer produces acetate from CO. The use of a two-step electrolyzer cascade allows for the spontaneous formation of (bi)carbonates to be avoided by using a neutral electrolyte in the CO_2 electrolysis step. Avoiding (bi)carbonate formation allows for improved stability and performance of the tandem electrolysis system toward acetate.[29] For the outlet acetate stream to be biocompatible, previous work has shown that in a traditional anion exchange membrane electrode assembly, the acetate-to-KOH ratio of the effluent must be above 0.4 to support food growth, and the effluent must be neutralized.[12] Alternatively, emerging reactor designs capable of electrochemically reducing CO_2 to acetic acid in pure deionized water could be utilized, but additional work is still needed to further develop this technology.[33,34] Once the acetate has been electrochemically produced from CO_2, it is fed to the final layer of the electro-ag system where food growth will occur without the need for light. The exogenously supplied acetate will support heterotrophic cultivation in a controlled environment without photosynthetic inputs. It is estimated that a typical electro-ag system will be 3–7 stories (~10–23 m) high depending on the food type produced (see experimental procedures). Some crops, such as maize, can grow up to a story high, while others, like lettuce, can be easily stacked into multiple layers within a single story. To date, this electro-ag system has already demonstrated a 4-fold improvement in energy efficiency for biomass production compared to photosynthetic crop growth, and further improvements are well within reach.[12]

ENVIRONMENTAL AND ECONOMIC ADVANTAGES OF ELECTRO-AGRICULTURE

The global food system is currently built upon photosynthesis to produce food directly from crops or from livestock that consume photosynthetic crops. The efficiency of converting solar energy to food is lowest for animal products due to the need to convert energy between multiple trophic levels, which requires animals to consume many more calories than they produce (Figure 3A). The typical crop plant retains >50× more solar energy as food than cattle since much of the original solar energy is lost while moving up the food chain (see experimental procedures). Thus, a key strategy for reducing the environmental impact of agriculture has been to create products from plants to replace meat. The plant-based meat industry has rapidly progressed with a 23.9% cumulative annual growth rate and a global market size of over $5 billion in 2023.[37] Similar trends are also being observed in plant-based replacements for egg and dairy products. However, the energy efficiency of all plant-based products has still been limited to just ~1% by photosynthesis until recently. The emergence of electro-ag has demonstrated that at least 4% energy efficiency is achievable. By using electro-ag to create alternatives to animal products, the efficiency gains offered by plant-based products could be amplified. For example, electro-ag would enable a plant-based burger to be >200× more efficient than beef rather than 50× more efficient than beef when that same plant burger is produced using ingredients derived from photosynthesis. This improved energy efficiency would enable a massive reduction in greenhouse gas emissions and natural resources required to feed the human population.

The United States currently uses more than half of its land for agriculture. By improving the energetic efficiency of farming via electro-ag, immense reductions

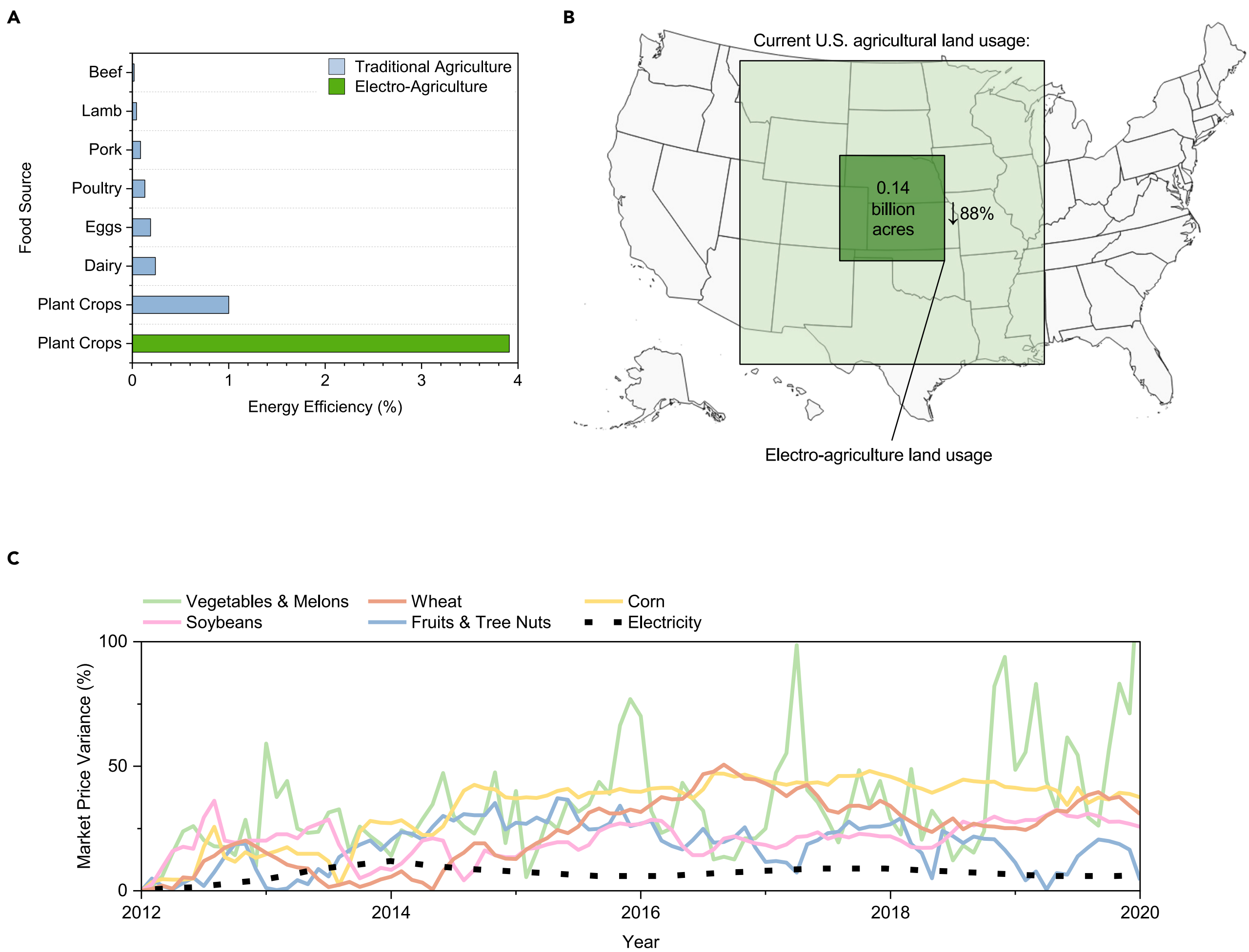

Figure 3. Sustainability and economic analysis

(A) Energy efficiency of food production by food source (see calculations in experimental procedures).

(B) Land usage of traditional and electro-ag food systems in the US (drawn to scale).

(C) Market price variance of traditional food crops vs. industrial electricity.[35,36]

in agricultural land usage can be achieved. If all the food in the United States was produced via electro-ag, the total land usage for farming could be reduced by 88% from 1.2 billion acres down to just 0.14 billion acres (see calculation in experimental procedures). This would free up over 1 billion acres for rewilding to restore natural ecosystems that existed prior to human intervention. Much of this rewilded land could help expand the 800 million acres of United States forestland, which currently sequesters 776 million metric tons of CO_2 annually in the United States (12% of the United States greenhouse gas emissions).[38] Thus, electro-ag would allow for both ecological restoration and natural carbon sequestration at a massive scale.

In addition to environmental benefits, electro-ag could help stabilize food prices. As weather becomes more unpredictable in a rapidly changing climate, maintaining a stable market price for food will become more challenging. Developing nations are particularly susceptible to food insecurity driven by price volatility. Global food price spikes in the wake of the COVID-19 pandemic led to nearly $^1/_3$ of the global population lacking adequate access to food in 2020.[39] Despite growing global food production per capita,[40] the global south is becoming disproportionately reliant on food imports under worsening climate conditions, making them more vulnerable to food price spikes.[41] Fortunately, industrial electricity has a relatively low market price variance compared to food crops (Figure 3C). Thus, electrifying agriculture would help stabilize a volatile food market, minimizing future food price spikes. The deployment of electro-ag in a region like Africa that disproportionately suffers from food price spikes offers great promise to improve the region's food system. In Africa, a cheap, reliable source of electricity to power electro-ag is accessible via solar photovoltaics. An acetate reservoir could be replenished during the day while food crops grow around the clock completely independent of light access or weather. Electro-ag also allows for food production to be localized, allowing for a streamlined supply chain and insulation from foreign exchange rate volatility. These benefits are maximized when all feedstocks, including fertilizer, can be produced locally. The localization of food production also fosters community empowerment, nurtures the self-sufficiency of local economies, enhances food freshness, and reduces the carbon footprint of food transport.

FUTURE DIRECTIONS AND OUTLOOK

Today, electro-ag has been demonstrated to convert 4% of solar energy to biomass, a 4-fold improvement over traditional photosynthetic agriculture (Figure 4A). Despite recent progress in developing electro-ag, many key hurdles to commercialization remain. The technology readiness level of electro-ag is still too low to accurately assess production cost, but given the relatively low market price of staple crops, it will be difficult for electro-ag to be economically deployed at scale in the near future. In the near term, electro-ag is most useful for scenarios where it is otherwise too difficult to produce food via photosynthesis. However, even in these scenarios, electro-ag requires access to relatively large amounts of electricity. If renewables are used, future work is still needed to improve the intermittent operation of the electrolysis system, or energy storage systems must also be deployed. Advancements in solar photovoltaics, electrolyzer performance, and genetic engineering could help improve the efficiency of electro-ag in the future to reduce electricity usage. Commercial solar photovoltaics operate at ~22% energy efficiency today with utility-scale systems producing energy cheaper than any other energy source at $0.037 USD/kWh.[42] Solar photovoltaics have recently made great advances, achieving a record 47.6% energy efficiency[43] with the United States Department of Energy now targeting a solar energy production cost of $0.02/kWh by 2030.[44] Thus, the energy efficiency of commercially available solar photovoltaic systems is expected to only continue improving in the future. If 48% solar photovoltaic energy efficiency can be achieved commercially, it would improve the total energy efficiency of electro-ag to 7.9%, offering nearly an 8-fold improvement over photosynthesis.

In addition to the advancements in solar photovoltaics, CO_2/CO electrolysis technology is also rapidly improving. Great advances in electrolyzer performance have been made by demonstrating a CO-to-acetate Faradaic efficiency of up to 91%.[45] Critically, the quality of the acetate stream at the electrolyzer outlet has also been improved with up to 7.6 M acetate produced at >99% purity, which substantially reduces the need for downstream processing and purification.[29] Additionally, porous solid electrolyte systems have been developed to produce acetic acid in a salt-free stream, which helps improve direct biocompatibility.[46] The scalability of tandem CO_2 electrolysis systems for producing acetate has also been recently illustrated with the first kW-scale system demonstrating relatively stable operation and comparable performance to Watt-scale systems.[47] By enhancing electrolyzer performance,

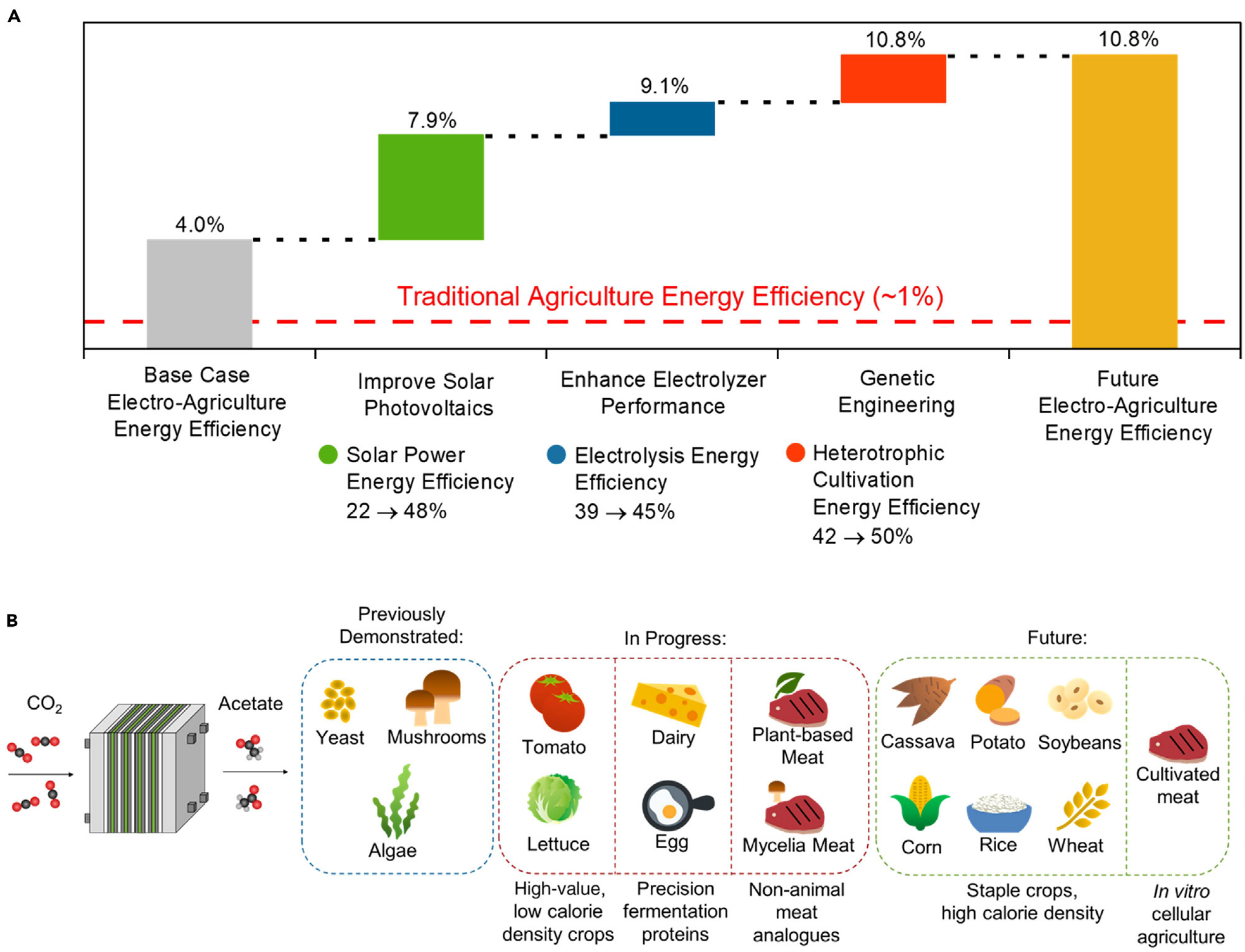

Figure 4. Future directions for electro-ag

(A) Pathway for improving electro-ag efficiency.

(B) Expanding the repertoire of electro-ag food products to high-value plants, staple crops, and proteins.

efficiency could be increased from 39% to 45%. This improvement, when combined with advancements in solar photovoltaic technology, could raise the overall energy efficiency of electro-ag to 9.1%. Improving electrolyzer efficiency will be critical given that feeding the entire US using electro-ag would require ~19,600 TWh/year to produce 1.1 billion tons of acetate using current tandem CO_2 electrolysis technology (see experimental procedures). This would require new renewable electricity infrastructure to be built at about 5× the current scale of current US electricity consumption (4,000 TWh/year).[48] Another critical challenge for renewably powered CO_2 electrolysis is stability under intermittent operation. 500 h of relatively stable performance has been demonstrated under dynamic power supplies mimicking solar photovoltaics, but additional stability improvements are still needed.[49] It should be noted that continuous heterotrophic growth can still be achieved under an intermittent power supply by generating an acetate reservoir when electricity is available. In addition to improving CO_2 electrolysis technology, genetic engineering techniques, such as CRISPR and other gene-editing tools, can be utilized to optimize the energy efficiency of heterotrophic cultivation. By refining the metabolism of acetate (used as both a carbon and energy source), metabolic efficiency could be elevated from 42% to ~50%. These genetic modifications, paired with

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improvements in solar photovoltaics and electrolysis systems, could potentially increase electro-ag's energy efficiency to 10.8%. This represents a 10-fold improvement over traditional photosynthesis and nearly triples the energy efficiency previously demonstrated in electro-ag systems.

An important factor to consider is that the need for carbon capture to supply CO_2 to the electrolysis system is highly scenario dependent. For space applications, CO_2 would be sourced from the Environmental Control and Life Support System on a space shuttle or extracted directly from the Martian atmosphere (95.0% CO_2, 2.8% N_2, and 2.1% Ar)[50] on a Mars base. For terrestrial applications, early deployment would likely rely upon point source capture, increasing the total energy needed for the CO_2 electrolysis system by only about 1% (see experimental procedures), which would have a relatively small impact on total land usage and electro-ag efficiency. If all US CO_2 emissions related to industrial energy sources were captured today, it would supply enough CO_2 for electro-ag to support 56% of the amount of biomass currently consumed in the US (see experimental procedures). However, as decarbonization efforts are implemented and point sources of CO_2 are eliminated, large-scale electro-ag will likely require CO_2 to be sourced from direct air capture. Direct air capture would also be needed in remote environments that lack CO_2 point sources. Direct air capture requires about 2,000 kWh ton^{-1} to overcome the mass transport limitation associated with extracting CO_2 from the 400 ppm concentration in air. This is an order of magnitude larger than the energy consumption demonstrated by point source capture technology, and much work is still needed approach the theoretical minimum energy usage (126 kWh ton^{-1}) of direct air capture. Today's state-of-the-art direct air capture technology would increase the total energy usage of transforming CO_2 into acetate by 17.5% (see experimental procedures). This would decrease the solar-to-food efficiency improvement of electro-ag over photosynthesis from 4× to ~3× but would only increase total land usage by 1.4% in the most extreme land-intensive scenario.

While improvements in solar-to-food energy efficiency are being made, parallel research to expand the repertoire of food crop varieties capable of growing on acetate while also increasing the edible fraction of plant biomass is ongoing. Electro-ag has achieved previous success with mushrooms, algae, and yeast, but other organisms are also capable of utilizing acetate and simply require metabolic improvement.[51] Preliminary success has been achieved with lettuce, rice, canola, pepper, and tomato.[12] Initial efforts are focused on pursuing high-value crops from electro-ag like lettuce and tomatoes (Figure 4B). Electro-ag also offers the opportunity to produce egg and dairy proteins from acetate-fueled precision fermentation.[52] Future electro-ag efforts could enable acetate or other electrochemicals to serve as carbon sources in growth media for cultivating animal cells *in vitro* to produce cultured meat. Future work will also focus on producing high-calorie staple crops via electro-ag, particularly cassava, sweet potatoes, and grain crops, which are widely consumed throughout Africa. On average, grain crops are ~50 wt % edible biomass,[53–55] meaning that a 1% photosynthetic solar-to-total biomass efficiency results in ~0.5% efficiency toward edible biomass. Without the need for crops to photosynthesize, certain inedible components of these plants are no longer necessary. Crops can be bred or genetically engineered to redirect energy from unnecessary leaves and stems to edible parts, increasing the consumable portion of the plant to over 75 wt %. Generating staple crops with enhanced edibility via electro-ag is critical to improving solar-to-edible biomass efficiency. This approach can improve crop yields for regions where farming is most threatened by the climate crisis. Thus, developing these enhanced crops is essential for the equitable deployment of electro-ag. This technology presents an opportunity to reinvent agriculture from the ground up, and it must be thoughtfully developed and deployed to avoid perpetuating the inequities that currently exist in today's global food system.

CONCLUSION

Using the same primary inputs as photosynthesis (CO_2, sunlight, and water), electro-ag offers at least a 4-fold improvement in solar-to-food efficiency over traditional farming. By converting CO_2 to acetate using renewable solar photovoltaics and organisms capable of heterotrophic growth on acetate, electro-ag has pioneered a new frontier in food production. The limitations of photosynthetic efficiency that have constrained agricultural practices for millennia can now be overcome. This innovative approach to food production offers the opportunity to reimagine the global food system to become more sustainable. In the United States, an 88% reduction in agricultural land usage could be achieved through the implantation of electro-ag. This would allow for the opportunity to restore natural ecosystems on nearly half of the nation's land mass, naturally sequestering CO_2 in the rewilded habitats. Additionally, food price spikes can be avoided by establishing a food system in a controlled environment that is less susceptible to increasingly severe weather, droughts, and flooding due to a rapidly changing climate. We propose a pathway toward improving the energy efficiency of electro-ag to 10.8% by identifying advances in solar photovoltaics, electrolyzer performance, and genetic engineering. Future developments in electro-ag should focus on calorie-dense staple crops and the production of alternative proteins to maximize its impact in food-insecure regions like Africa. Electro-ag is a radical reconception of the global food system that offers meaningful progress toward resolving both climate change and world hunger.

EXPERIMENTAL PROCEDURES

Max conversion efficiency and stoichiometry for acetate conversion to biomass

The calculation of max conversion efficiency was adapted from a previously reported method.[56] Biomass of an organism that is proficient at consuming acetate, like yeast, has the chemical formula $C_5H_{8.3}O_{2.7}N_{0.7}$.[57] This has a molecular weight of 121.4 g/mol. The yield of dry cell weight (DCW) per electron from electron carriers (e.g., NADH and $FADH_2$) produced from a molecule has been estimated as 3.14 g DCW per electron (e^-). When metabolized, acetate produces 3 NADH molecules and one $FADH_2$, each of which carries two electrons for a total of 8 electrons. The conversion of these electrons to biomass using the estimate from Shuler and Kargi[58] is expressed stoichiometrically below:

$$\frac{3.14\ g\ DCW}{e^-} \times 8\ e^- = 25.1\ g_{DCW}\ mol_{acetate}{}^{-1} \quad \text{(Equation 1)}$$

$$\frac{25.1\ g\ DCW}{121.4\ g/mol\ biomass} = 0.21\ mol\ biomass \quad \text{(Equation 2)}$$

$$CH_3COOH \rightarrow 0.21 C_5H_{8.3}O_{2.7}N_{0.7} + 0.95 CO_2 \quad \text{(Equation 3)}$$

The moles of CO_2 produced were determined by subtracting the carbon moles in biomass from the carbon moles in acetic acid:

$$2\ mol\ C - (0.21\ mol\ biomass \times 5\ mol\ C) = 0.95\ mol\ CO_2 \quad \text{(Equation 4)}$$

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The efficiency of acetate to biomass can be calculated through the moles of carbon on each side of the equation not in CO_2:

$$\frac{(0.21\ mol\ biomass \times 5\ mol\ C)}{2\ mol\ C} \times 100\% = 52.5\% \qquad \text{(Equation 5)}$$

Energy efficiency calculations

The animal agriculture energy efficiencies in Figure 3A were determined by factoring in the efficiency of plant growth to the energy feed conversion efficiency of each animal product. This allowed for the conversion of solar energy to plants to animal food products to be fully captured. For example, the energy conversion of feed to edible beef is reported at 1.9%,[59] and solar energy conversion efficiency for producing the plant feed consumed by cattle is ~1%.[12] Thus, the following equation can be used to determine the solar-to-food conversion efficiency of beef:

$$1.9\%\ feed\ to\ edible\ beef\ conversion \times 1\%\ conversion\ of\ sunlight\ to\ feed = 0.019\%\ solar\ energy\ to\ food\ efficiency \qquad \text{(Equation 6)}$$

Similar calculations were repeated for all other animal products using previously reported feed to animal product conversion efficiencies.[59]

These calculations indicate that the efficiency of photosynthetic plant crops is over 50× greater than cattle at converting sunlight to food:

$$\frac{1\%\ photosynthetic\ solar\ to\ food\ efficiency}{0.19\%\ cattle\ solar\ to\ food\ efficiency} = 52.6 \qquad \text{(Equation 7)}$$

To calculate the total solar-to-food energy efficiency of the electro-ag system, the following calculation was performed based upon a solar-to-electricity efficiency of 22% in solar photovoltaics, an electricity-to-acetate efficiency of 39% via CO_2 electrolysis, and 42% heterotrophic cultivation efficiency:

$$0.22 \times 0.39 \times 0.42 \times 100\% \approx 4\%\ solar\ to\ food\ efficiency \qquad \text{(Equation 8)}$$

The acetate-to-biomass efficiency was determined based upon previously published results of algae grown on acetate[12] using the equation shown below:

$$Y_{biomass/acetate} \times \frac{\Delta H^{\circ}{}_{biomass}}{\Delta H^{\circ}{}_{acetate}} = 0.2831 \frac{g\ biomass}{g\ acetate} \times \frac{21.5kJ/g}{14.58kJ/g} \times 100\% = 41.75\% \qquad \text{(Equation 9)}$$

Additional details can be found in our previously reported work.[12] To consider a scenario where carbon capture is a necessary component of the CO_2 electrolysis system, the energy usage of direct air capture needs to be accounted for. To achieve this, the mass of acetate produced per gram of CO_2 must be calculated as shown below:

$$\frac{55.04 g_{acetate}\ mol^{-1}}{\left(44.01 g_{CO_2}\ mol^{-1}\right) \times \left(2\ mol_{CO_2}\ mol_{acetate}{}^{-1}\right)} = 0.67\ g_{acetate}\ g_{CO_2}{}^{-1} \qquad \text{(Equation 10)}$$

It has previously been reported that 61.36 kJ is required to produce 1 g of acetate in a tandem CO_2 electrolysis system.[12] Climeworks has reported that their direct air capture units require 2,000 kWh per ton CO_2.[60] The increase in energy usage of the electrolysis system when direct air capture is considered is shown below:

$$carbon\ capture\ energy\ usage = \frac{2000\ kWh}{ton_{CO_2}} \times \frac{3600\ kJ}{1\ kWh} \times \frac{1\ ton}{1 * 10^6\ g} \times \frac{1\ g_{CO_2}}{0.67\ g_{acetate}} = 10.75\ kJ\ g_{acetate}{}^{-1} \qquad \text{(Equation 11)}$$

Thus, the use of direct air capture increases the total energy usage of the tandem CO_2 electrolysis system by 17.5% as shown below:

$$\frac{10.75\ kJ\ g_{acetate}}{61.36\ kJ\ g_{acetate}} \times 100\% = 17.5\% \qquad \text{(Equation 12)}$$

Based on the calculations shown above, when direct air capture energy usage is lumped into the energy consumption associated with CO_2 electrolysis, the total efficiency of converting CO_2 to acetate decreases from 39% to about 30% and the overall solar-to-food efficiency of electro-ag decreases from 4% to 2.8%. Alternatively, point source capture can be used to capture CO_2 from concentrated industrial emission sources, which requires substantially less energy (~100 kWh ton^{-1}).[61] Following the same calculations shown above, point source capture only results in about a 1% increase in total energy consumption for the CO_2 electrolysis system.

Maximum CO_2 consumption calculations

To estimate the total amount of CO_2 required to feed the US population using electro-ag, the annual US biomass consumption was first identified to be 1996 lbs. per person.[62] Thus, the total amount of biomass consumed in the US each year can be calculated as shown below:

$$Total\ Annual\ U.S.\ Biomass\ Consumption = \frac{1996\ lbs.\ biomass\ anually}{person} \times 333.3\ million\ people \times \frac{1\ kg}{2.2\ lbs.} \times \frac{1\ metric\ ton}{1,000\ kg} = 302\ million\ metric\ tons\ biomass\ per\ year \qquad \text{(Equation 13)}$$

The total CO_2 emissions from powering the US industrial sector in 2023 was 963 million metric tons.[63] Assuming that all of these emissions could be captured at a point source, the total amount of acetate that could be produced from these emissions via electro-ag can be calculated:

$$963\ million\ metric\ tons\ CO_2 \times \frac{0.67\ ton_{actate}}{ton_{CO_2}} = 645\ million\ tons\ acetate \qquad \text{(Equation 14)}$$

Once the total amount of acetate that can be made from industrial point sources of CO_2 has been calculated, the amount of biomass that can be produced from this acetate can be determined based upon the previously calculated acetate-to-biomass conversion efficiency and assuming 50% of the produced biomass is edible based upon farm indices for common staple crops:[53–55]

$$645\ million\ tons\ acetate \times 0.525 \times 0.5 = 170\ million\ tons\ biomass \qquad \text{(Equation 15)}$$

Thus, the total amount of biomass produced via electro-ag using US industrial CO_2 point sources is 170 million tons, which is 56% of the current 302 million metric ton annual US demand. The authors acknowledge that this is a simplified estimate given the widely varying caloric density of biomass, but this calculation offers some insight into the scale of point source CO_2 needed to feed the US using electro-ag.

Acetate and energy usage calculations

Using the previously calculated 302 million metric tons of biomass consumed annually in the US along with the previously calculated 52.5% conversion efficiency of acetate to biomass and a 50% farm index (edible fraction of biomass),[53–55] the total amount of acetate per year required to feed the US can be determined:

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$$\frac{302\ million\ tons\ biomass}{year} \times \frac{1}{0.525} \times \frac{1}{0.5} = 1,150\ million\ tons\ acetate\ year^{-1}$$ (Equation 16)

It should be noted that this is a simplified estimate given the widely varying caloric density of biomass. Previous work has shown that the theoretical thermodynamic energy required to produce 1 g of multi-carbon products such as acetate from CO_2 is 21.86 kJ.[12] However, due to overpotential, the best performance reported for integrated tandem CO_2 electrolysis toward acetate is 61.36 kJ for 1 g of product.[12] This allows for the total amount of electricity required to produce enough acetate to feed the US via electro-ag to be determined:

$$\frac{1,150\ million\ tons\ acetate}{year} \times \frac{1 * 10^{12}\ g}{1\ million\ tons} \times \frac{61.36\ kJ}{1\ g_{acetate}} \times \frac{1\ kWh}{3600\ kJ} \times \frac{1\ TWh}{1 * 10^{9}\ kWh} \approx 19,600\ TWh\ year^{-1}$$ (Equation 17)

Land usage calculations

The land usage for a scenario where all food in the United States was produced via electro-agriculture that is depicted in Figure 3B was determined by first establishing that 52% of United States' land area (1.2 billion acres) is currently used for agriculture.[64] A shift to a food system composed entirely of electro-agriculture plant crop production would replace animal products with substitutes and reduce losses in efficiency by avoiding multiple trophic levels. A 76% reduction in agricultural land usage could be achieved with a diet that excludes conventionally produced animal products by eliminating both the land used by livestock and the land for growing livestock feed.[8] Electro-agriculture has previously demonstrated a 4-fold improvement in energy efficiency for producing plant crops compared to traditional photosynthesis, offering an additional 75% reduction in land usage.[12] Therefore, the total land usage for electro-agriculture can be calculated with the following equation, assuming 50% of the biomass is edible based upon typical farm indices for staple crops:[53–55]

$$\frac{1.2\ billion\ acres \times (1 - 0.75) \times (1 - 0.76)}{0.5} = 0.14\ billion\ acres$$ (Equation 18)

To estimate the land usage required when relying upon direct air capture to supply CO_2 to the electrolysis system, the total amount of CO_2 to feed the US population with electro-ag must be determined. This can be calculated using the previously determined need for 575 million tons of acetate per year to feed the US via electro-ag:

$$\frac{1,150\ Mt_{actate}}{year} \times \frac{ton_{CO_2}}{0.67\ ton_{actate}} = 1,716\ Mt_{CO_2}\ year^{-1}$$ (Equation 19)

The minimum land requirement to capture 1 Mt CO_2 per year for Climeworks Mammoth plant is 220 acres.[65] This can be used to determine the total land usage required for direct air capture:

$$\frac{220\ acres}{Mt_{CO_2}\ year^{-1}} \times \frac{1,716\ Mt_{CO_2}}{year} \approx 377,520\ acres$$ (Equation 20)

The land usage needed to power direct air capture varies widely by source, but a more extreme land-intensive scenario is provided here by assuming the direct air capture plants would be solar powered. It has been previously estimated that 8 km^2, or ~1,977 acres are required to capture and compress 1 Mt CO_2 from air.[65]

Based upon this, the total land needed to power enough direct air capture to feed the US can be determined:

$$\frac{1977\ acres}{Mt_{CO_2}\ year^{-1}} \times \frac{1716\ Mt_{CO_2}}{year} \approx 3.4\ million\ acres \quad \text{(Equation 21)}$$

When combined with the previously calculated land usage for the direct air capture units themselves (377,520 acres), there are about 3.5 million additional acres for solar-powered direct air capture. In total, an electro-agriculture system using direct air capture would require 0.1435 billion acres of land to feed the entire US. Thus, the total reduction in land usage achieved with electro-agriculture can be determined:

$$\frac{1.2 - 0.1435\ billion\ acres}{1.2\ billion\ acres} \times 100\% = 88\%\ reduction\ in\ land\ usage \quad \text{(Equation 22)}$$

Theoretical minimum energy usage of direct air capture

It has previously been reported that the theoretical minimum work required to concentrate 400 ppm CO_2 in air to 99% purity CO_2 in one stream and release 200 ppm CO_2 in a second stream is about 20 kJ mol_{CO2}^{-1}.[66] This minimum energy requirement can be converted to kWh ton_{CO2}^{-1} as shown below:

$$\frac{20\ kJ}{mol_{CO_2}} \times \frac{1\ mol_{CO_2}}{44.01\ g} \times \frac{1 * e^6\ g}{1\ ton} \times \frac{1\ kWh}{3600\ kJ} = 126\ kWh\ ton_{CO_2}^{-1} \quad \text{(Equation 23)}$$

Scale matching case study

Given 1 m^2 of land area, the energy transfer through each layer of the electro-ag system can be analyzed for producing staple crops. Although multiple sources of electricity can be used in electro-ag, the first layer in this case study is assumed to be composed of solar photovoltaics. The average amount of solar energy striking the surface of the Earth is 342 watts/m^2 each year.[67] Thus, assuming 22% solar photovoltaic efficiency, the amount electricity supplied to the electrolyzer in a 1 m^2 land area is shown below:

$$\frac{342\ W}{m^2\ yr^{-1}} \times 0.22 \times \frac{8760\ h}{yr} \times \frac{1\ kWh}{1,000\ Wh} = 659\ kWh\ m^{-2} \quad \text{(Equation 24)}$$

It has previously been demonstrated that producing acetate via tandem CO_2 electrolysis requires 61.36 kJ/g in addition to 10.75 kJ/g for direct air capture to supply CO_2 to the electrolysis system.[12,60] This can be used to determine the amount of acetate that can be produced via tandem CO_2 electrolysis using the electricity provided from solar photovoltaics in a 1 m^2 area:

$$\left(61.36\ kJ\ g^{-1} + 10.75\ kJ\ g^{-1}\right) \times \frac{1\ kWh}{3600\ kJ} \times \frac{1,000\ g}{1\ kg} = 20\ kWh\ kg^{-1}_{acetate} \quad \text{(Equation 25)}$$

$$\frac{659\ kWh\ m^{-2}}{20\ kWh\ kg^{-1}_{acetate}} = 33\ kg\ acetate\ m^{-2} \quad \text{(Equation 26)}$$

To determine if a tandem CO_2 electrolysis system capable of producing 33 kg of acetate per year is capable of fitting within 1 m^2 area, recently published work on kW-scale tandem CO_2 electrolysis can be used to estimate the footprint of electrolyzers.[47] Based on this work, 2 sets of 10 vertically stacked cells with an active area of 100 cm^2 per cell are required to produce 1 kg acetate per day. Therefore, the minimum area requirement for a stack producing 33 kg acetate per year can calculated:

$$\frac{33\ kg\ acetate}{year} \times \frac{1\ year}{365\ days} \times \frac{100\ cm^2}{1\ kg\ day^{-1}} \times 2\ sets \times \frac{1\ m^2}{10,000\ cm^2} = 0.002\ m^2$$

(Equation 27)

Therefore, the tandem CO_2 electrolysis hardware requires only 0.002 m^2 of area to utilize the electricity produced from 1 m^2 of solar photovoltaics, leaving sufficient space for pumps, storage tanks, and other auxiliary equipment in the electrolysis layer.

Given 33 kg of acetate produced per year, the amount of biomass produced from this acetate can be determined:

$$\frac{33\ kg\ acetate}{m^2} \times 0.2831 \frac{kg\ biomass}{kg\ acetate} = 9.34\ kg\ biomass\ m^{-2} \quad \text{(Equation 28)}$$

The average amount of biomass produced in 1 m^2 among 2 common staple crops, maize and triticale (wheat/rye hybrid), has been reported to be 1.60 $kg_{biomass}\ m^{-2}$ per year.[68] This indicates a 5.8× increase in biomass yield per area for these specific crops:

$$\frac{9.34\ kg_{biomass}\ m^{-2}}{1.60\ kg_{biomass}\ m^{-2}} = 5.8 \quad \text{(Equation 29)}$$

This case study analysis is only representative of maize and triticale, which have yet to be demonstrated in electro-agriculture, and does not fully account for the land footprint of carbon capture; thus, it should not be used to broadly estimate land usage for all food production using an electro-agriculture system. However, this case study provides some insight into how much solar energy can be translated into food within a given land area. This analysis also confirms that a given area of solar photovoltaics provides sufficient electricity for producing relatively large qunantities of acetate that leads to substantial improvements in crop yields per area. Additionally, this analysis can be used to estimate the height of an electro-ag system. Given that some crops, such as maize, can grow up to a story high, this indicates that the maximum number of floors required for heterotrophic food growth is 6 (rounding up from 5.8). With an additional floor required for the electrolysis system and the roof utilized for solar photovoltaics, the total maximum number of floors required is 7 (∼23 m). However, many crops, such as lettuce, are relatively short, and multiple layers of plant growth can be stacked on a single floor. If it is assumed that 3 layers of crops could be stacked per floor, then the minimum height requirement for an electro-ag system is 3 total floors (∼10 m).

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AUTHOR CONTRIBUTIONS

F.J. and R.E.J. supervised and helped conceive this work. B.S.C. and M.H.-D. contributed equally to prepare the first draft of the manuscript. All authors edited and approved the final version of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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