

Prospects and Challenges for Solar Fertilizers

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Abstract

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Keywords: Science, Publication, Complicated

1. Introduction

The Haber-Bosch process for thermochemical synthesis of ammonia from nitrogen and hydrogen transformed the global fertilizer industry and was a critical enabler of the continued expansion of human populations [?]. The process is an impressive feat of modern chemical engineering, producing around 150 million tons of ammonia per year at a thermodynamic efficiency of up to 70% [? ?]. However, the process also has downsides. The scale of the process leads to massive energy consumption of 2.5 exajoule per year,

9 and the hydrogen feedstock is typically obtained via methane reforming,
10 leading to a tremendous carbon footprint of 340 Mt of CO₂ equivalent per
11 year; this is the highest impact of any commodity chemical production [?
12]. Furthermore, the high temperatures (~ 700 K) and pressures (~ 100 bar)
13 lead to substantial capital cost and favorable economies of scale, driving
14 highly centralized production. This is in contrast to the decentralized use of
15 ammonia-based fertilizers, which results in substantial transportation costs
16 and additional emissions. This is particularly impactful in remote locations
17 such as sub-Saharan Africa, where soils are often nutrient-limited due to lack
18 of access to fertilizers[? ?]. The opposite problem of over-fertilization also
19 has a substantial environmental impact in more developed nations due to
20 the periodic application of highly concentrated fertilizers that cause nitrate
21 pollution in groundwater through leaching. Finally, the intense conditions
22 and reactive nature of concentrated ammonia lead to safety and national
23 security concerns, as evidenced by massive explosions at fertilizer plants and
24 the common use of fertilizers in makeshift explosives.

25 One possible strategy to overcome these disadvantages is decentralized
26 production of fertilizers using solar energy. These “solar fertilizers” could
27 harness solar energy, nitrogen, and water/oxygen from the air to produce
28 lower-concentration ammonia- or nitrate-based fertilizers at or near the point
29 of use. This is advantageous from the perspective of solar energy capture
30 since the intermittent energy is directly captured in a storable product that
31 can be utilized near the point of production, avoiding issues with electricity
32 storage and transport [?]. There are also advantages from an agricultural
33 perspective, since inexpensive feedstocks and reduced transport costs may
34 significantly improve access to fertilizers in remote and developing regions,
35 and the use of lower-concentration fertilizers may also enable novel strategies
36 of nutrient management that can reduce groundwater pollution. Further,
37 low-concentration fertilizers produced at ambient conditions are inherently
38 safer both from the perspective of the process and the product.

39 Solar fertilizers hold substantial promise as a route to solar energy capture
40 and sustainable agriculture, but there are also considerable challenges. One
41 critical and obvious challenge is in the development of a viable strategy for
42 efficiently using solar energy to dissociate the strong dinitrogen triple bond at
43 ambient conditions. Nitrogen fixation at ambient conditions is a holy grail of
44 chemistry, and has been the subject of considerable research in homogeneous
45 catalysis, enzyme catalysis, and bioengineering, yet no viable strategies have
46 emerged due to issues with low conversion and/or stability under realistic

47 conditions [?]. More recently there has been a surge of interest in photo-
48 and electrocatalytic nitrogen fixation by heterogeneous catalysts []. This
49 route is particularly interesting from the perspective of solar fertilizers since
50 photoelectrochemical systems have the potential to scale relatively easily and
51 have been the subject of considerable research in the solar fuels community.
52 However, further work is needed to improve the yield and efficiency of photo-
53 and electrochemical nitrogen fixation.

54 Solar fertilizers are also expected to differ significantly from traditional
55 fertilizers, opening a range of additional agronomic challenges. One key dif-
56 ference is that solar fertilizers are expected to have considerably lower fixed
57 nitrogen concentrations, owing to the fact that photo(electro)chemical nitro-
58 gen fixation efficiencies are unlikely to compete with the 70% efficiency of
59 the Haber-Bosch process. Separating the ammonia would be energy inten-
60 sive and likely require centralized facilities, potentially mitigating the advan-
61 tages of decentralized solar fertilizer production. Direct utilization of dilute
62 fertilizers would avoid or reduce the amount of energy needed for separa-
63 tion/concentration, and may also enable more controlled nutrient manage-
64 ment. However, this represents a paradigm shift in agricultural practice, and
65 considerable effort is needed to understand how dilute solar fertilizers can be
66 integrated with agricultural systems. These considerations will also inform
67 the development of the photo(electro)catalytic processes for solar fertilizer
68 production, and hence should be considered in parallel.

69 In this work we identify key considerations and performance targets for
70 the photo(electro)chemical production of dilute solar fertilizers from the per-
71 spective of catalysis and agronomics. Some specific advantages and disad-
72 vantages of decentralized dilute fertilizer production are outlined and the
73 potential agronomic impacts of varying levels of decentralization are exam-
74 ined. Initial quantitative performance targets are identified based on back-
75 of-the-envelope calculations and possible agricultural scenarios. Finally, the
76 tradeoffs between photo- and electrochemical routes to solar fertilizers are
77 briefly discussed, and some basic reactor design concepts are outlined. We
78 hope that these considerations will serve as a foundation and guide for fu-
79 ture research in the development of photo(electro)chemical processes for solar
80 fertilizer production.

2. Decentralized Dilute Fertilizers

The price of fertilizer is controlled by a complex interplay of geopolitical and economic factors. A detailed analysis is beyond the scope of this work, but we briefly introduce some key concepts. The cost of fertilizers can be broken down into production, transportation, and storage. The production cost of fertilizer is controlled primarily by the cost of natural gas used to produce hydrogen for the Haber-Bosch process, and hence varies with location and geopolitical factors. This dependence on natural gas also promotes centralized production, with most fertilizer plants located near natural gas deposits [?]. The cost of transportation is highly variable. Transportation costs as low as ??? % in the U.S. where ammonia pipelines and railroads connect fertilizer production facilities along the Gulf of Mexico to the agricultural centers in the Midwestern states, or as high as 25% in landlocked sub-Saharan African countries such as Uganda where fertilizers must be transported via ships to a port and subsequently via trucks to agricultural centers []. For countries without large-scale fertilizer production it is common to separate transportation costs into domestic and international, since international transportation is more expensive and sensitive to political factors such as tariffs. Finally, the cost of storage must also be considered, although it is generally less variable than transportation or production (??? no idea if this is true). Figure ??? shows a comparison of the percentage of fertilizer cost arising from each category in 2? 3? representative countries, illustrating the considerable economic impact of fertilizer transportation in the developing world. (I am envisioning 2-3 pie charts with size corresponding to total fertilizer cost and breakdowns of production/transportation/storage contributions)

The total price of fertilizer is not derived directly from its components. For example, the price of fertilizer in Thailand (\$ 287/ton) is roughly half the price of fertilizer in Mozambique (\$ 567/ton), but this difference cannot be attributed directly to any single category. One critical factor that controls this overall price is economy of scale. Larger agricultural markets such as Asia are able to more effectively distribute fixed costs of transportation across more units of fertilizer, translating to lower prices at the farm scale. This scale-up is not possible in less developed markets for a variety of reasons including port capacity and poor transportation infrastructure. Less developed markets are also subject to more uncertain demand owing to lack of access to capital by smallholder farmers and unpredictable implemen-

118 tation of government subsidies. Overall, these factors lead to the perverse
119 situation in which fertilizers are most expensive in the poorest places where
120 the need is greatest. This is a key factor in the distressing fact that world
121 hunger is currently increasing, with over 800 million people suffering from
122 undernourishment as of 2016 [?].

123 Notably, many of these economic and geopolitical factors could be allevi-
124 ated by decentralized fertilizer production from renewable resources. Lack of
125 dependence on natural gas would reduce volatility in production costs, and
126 producing fertilizer at or near the point of use would reduce transportation
127 costs and reduce the price dependence on economies of scale. Furthermore,
128 local production would improve certainty in fertilizer availability and reduce
129 the influence of external factors such as tariffs and subsidies. Agricultural
130 production has also been tied to general economic prosperity, and local fertil-
131 izer manufacturing industries in developing countries could spur substantial
132 economic growth [?].

133 The concept of decentralization is difficult to quantify in general [?],
134 but in this context we propose the decentralization should scale directly with
135 the total number of fertilizer production facilities. It is useful to examine
136 order-of-magnitude estimates of these quantities to assess the prospects of
137 decentralization. A recent report identified a total of 63 major fertilizer
138 production facilities based on data from the 10 largest producers of ammonia-
139 based fertilizers [?]. While this list may be incomplete, it is expected to be
140 on the correct order of magnitude. This should be normalized by the total
141 agricultural output, which we propose can be estimated by the total number
142 of farms or the total amount of arable land. Both numbers are difficult to
143 know exactly, but a 2014 report estimated the total number of farms to be
144 in excess of 570 million with a total area of around 4.9 billion hectares as
145 of 2010 [? ?]. This indicates that a single ammonia-based fertilizer plant
146 serves on the order of 10 million farms, or 100 million hectares of arable land.

147 There are a continuum of options for moving away from this highly cen-
148 tralized scenario. The most extreme alternative would be fully-decentralized
149 “farm-scale” fertilizer production, corresponding to roughly 1 fertilizer pro-
150 duction facility per farm (or per ~ 10 ha), an increase of ~ 7 orders of mag-
151 nitude in the total number of fertilizer production facilities. This would also
152 correspond to proportional decrease in the scale of production. The global
153 average nutrient load needed for fertilization is ~ 50 kg-N/(ha yr) [corre-
154 sponding to a capacity of ~ 500 kg-N/yr for farm-scale production. This can
155 be used to estimate the annual revenue expected based on the cost of fer-

156 tilizer per country. In this case, the economic incentives favor decentralized
 157 production in countries with high fertilizer prices. For example, the price of
 158 urea in Ghana in 1999 was approximately \$1100/MT, or \$ 2350/MT-N (urea
 159 is 46% N by weight). This corresponds to an expected annual revenue on
 160 the order of \$ 1200/year. This relatively modest number suggests that fully
 161 decentralized fertilizer production must have very low capital and operating
 162 costs, even in countries where the cost of fertilizer is very high. Further-
 163 more, the process must be sufficiently robust that specialized operators are
 164 not needed for operations or maintenance. This suggests that “frugal inno-
 165 vation” strategies [?] may be required for the development of inexpensive
 166 and robust processes for farm-scale fertilizer.

167 Less extreme alternatives would be “small-scale” or “medium-scale” fer-
 168 tilizer production facilities, which could serve on the order of 100 or 10,000
 169 farms respectively. As production becomes more centralized the economics
 170 will favor more capital investment and labor specialization, enabling develop-
 171 ment of more technically advanced processes. The small-scale facility would
 172 have a production capacity of 50 MT-N/yr, while a medium-scale facility
 173 would produce 5,000 MT-N/yr. Assuming capital costs similar to current
 174 ammonia production are economical (\sim \$1,000/MT-N), this corresponds to
 175 \$50,000 or \$5 M of capital expense, which is rather modest by the standards
 176 of chemical plant construction. Other scales are also possible, and we pro-
 177 pose the following relationship between capital cost and area of arable land
 178 served: $C_{capital} \approx \$50 \times A_{arable}$ where $C_{capital}$ is capital investment in dollars
 179 and A_{arable} is the arable land area in hectares. This analysis is overly simplis-
 180 tic this will vary considerably depending on the market price of fertilizer and
 181 the cost of operators, feedstock, and maintenance; however, it can provide
 182 an order-of-magnitude estimate regarding the type of process that may be
 183 feasible to serve a specific amount of land, or conversely the scale needed
 184 for a process given an estimate of capital investment. For example, electro-
 185 chemical processes are likely only feasible at small or medium scales, while
 186 photochemical processes may be possible at the farm scale. This is discussed
 187 further in Section 4.

188 The production of more dilute fertilizers will act as a competing force
 189 against centralization, as transportation costs will be higher for fertilizers
 190 with lower nitrogen content. Utilization of solar energy is expected to pro-
 191 duce fertilizers with much lower nutrient densities owing to the lower den-
 192 sity of solar energy and the challenges with low efficiency and selectivity in
 193 photo(electro)chemical nitrogen fixation. As discussed in Section 3 the re-

194 quired solar-to-ammonia efficiencies and nutrient concentrations are in prin-
195 ciple surprisingly low; however, these products differ substantially from ex-
196 isting fertilizers and present a number of challenges. As discussed in the
197 subsequent section we estimate that the dilute limit for fertilizers is ~ 1 wt%-
198 N in aqueous solution, although ~ 3 -5 wt%-N is likely necessary for practical
199 relevance. This is in contrast to typical solid urea fertilizers that are 47 wt%-
200 N, and hence much more economical to transport. For small- or medium-scale
201 production it would likely be necessary to separate or concentrate the fixed-N
202 product to concentrations comparable with existing products (20-40 wt%-N)
203 for transport or storage. This additional separation process would require
204 additional capital investment and operational costs. However, in the limit
205 of farm-scale decentralization transportation may be less of an issue, since
206 dilute fertilizer could be directly applied through irrigation systems. Even
207 at the farm-scale such dilute fertilizers would present challenges with stor-
208 age, and an irrigation system would be required for application. The latter
209 is a particular challenge for many smallholder farms in sub-Saharan Africa,
210 where only around 7% of farms are equipped with irrigation. Nonetheless,
211 these farms still present a sizable market, and the prospect of combined fer-
212 tilization/irrigation systems may favor investment in irrigation systems.

213 Despite these challenges, dilute fertilizers also offer some potential ad-
214 vantages. One enticing possibility is the prospect of improved nutrient man-
215 agement. Currently the fixed nitrogen in fertilizers is not utilized efficiently,
216 with 20-50% being lost to leaching or vaporization. This is more prevalent
217 in developed countries where fertilizers are inexpensive, and particularly in
218 the case of potent anhydrous ammonia fertilizers. These highly concentrated
219 fertilizers release nutrients too rapidly for plant uptake. Not only is this
220 inefficient, but it also results in pollution of groundwater by nitrates and
221 release of N_2O , one of the most potent greenhouse gases. The most common
222 strategy for mitigation of these effects is the development of coatings that aid
223 in controlled release of nutrients and enhance uptake efficiency. While effec-
224 tive, the use of dilute fertilizers offers a different strategy in which nutrients
225 are delivered at a controlled rate. However, substantial additional research
226 into agronomics and plant nutrition is required to determine the potential
227 of this strategy and identify the optimal nutrient concentration and applica-
228 tion profile. Another advantage of dilute fertilizers are their inherent safety
229 since they will be less corrosive and more difficult to convert into explosives.
230 These factors suggest that further research into the utility and effectiveness
231 of dilute fertilizers is relevant to the field of solar fertilizers.

232 3. Preliminary Performance Targets

233 There has been a substantial recent increase in photo(electro)chemical
 234 nitrogen fixation research, yet there are no targets for how efficient these
 235 processes need to be. In this section we briefly outline targets for solar-to-
 236 ammonia efficiency, total fixed nitrogen concentration, and required rates of
 237 nitrogen fixation that have the potential to enable solar fertilizer production.
 238 These targets are not meant to be authoritative, but rather provide guidelines
 239 for catalyst development and fertilizer testing.

240 One key consideration is the overall efficiency required to convert solar
 241 energy to fertilizer. First, we estimate the areal energy density required
 242 for fertilization based on an assumption of 50 kg-N/(ha yr) provided by
 243 ammonia-based fertilizers:

$$50 \frac{\text{kg}_\text{N}}{\text{ha} \cdot \text{yr}} \times \frac{10^3 \text{ mol}_{\text{NH}_3}}{14 \text{ kg}_\text{N}} \times \frac{667 \text{ kJ}}{2 \text{ mol}_{\text{NH}_3}} \times \frac{1 \text{ ha}}{10^4 \text{ m}^2} \times \frac{1 \text{ yr}}{3.15 \times 10^7 \text{ s}} = 3.77 \frac{\text{mW}}{\text{m}^2} \quad (1)$$

244 this remarkably low energy density is roughly 6 orders of magnitude below
 245 the solar constant of 1000 W/m², indicating that high efficiencies are not
 246 necessary. An initial estimate can be obtained by assuming 8 hours of full
 247 sunlight per day and 1% of arable land dedicated to solar capture [?]. In this
 248 case the average solar flux is 333 W/m² and the corresponding required solar-
 249 to-ammonia efficiency is ~0.1 %. Data on actual average solar fluxes reveals
 250 that they vary from 120 - 280 W/m² depending on latitude [?], and there is
 251 also considerable variability in the nutrient load required, ranging from 15-
 252 200 kg-N/m² depending on a myriad of factors including crop and soil type.
 253 Based on these estimates the required solar-to-ammonia efficiency may range
 254 from 0.05 - 1.25 % depending on solar flux and required nutrient load. These
 255 estimates assume that 1% of arable land is dedicated to solar capture, and
 256 will vary linearly with the percentage of land available. We propose that 1%
 257 is a relatively conservative number, corresponding to 100 m²/ha or roughly
 258 6 typical solar panels per hectare. Notably, solar-to-ammonia efficiencies
 259 as high as 0.02 % have been reported for nitrogen fixation photocatalysts,
 260 suggesting that the efficiency target is feasible with further research.

261 In addition to efficiency it is also critical to consider the concentration of
 262 fixed nitrogen needed for a product to be considered a fertilizer. The limit-
 263 ing case can be determined by assuming that the nutrients will be included
 264 directly in the irrigation lines. However, the amount of irrigation needed is
 265 highly variable depending on crops, rainfall, location, and socioeconomic fac-
 266 tors (<http://www.fao.org/docrep/u5835e/u5835e04.htm>). Nonetheless, we

267 propose an estimate of 1500 L/ha/y as a typical number for practical sce-
 268 narios. Further, we note that while 50 kg-N/(ha yr) is a typical nitrogen
 269 nutrient load, the critical lower boundary for nutrient consumption can be as
 270 low as 15 kg-N/(ha yr). From these estimates we propose a lower boundary
 271 of 1 kg-N/L, or 1 wt % N, as a convenient estimate for the minimum nitrogen
 272 concentration that can be considered a fertilizer. This is roughly 1 order of
 273 magnitude lower than existing aqueous fertilizers, but it is 5-8 orders of mag-
 274 nitude above the concentrations reported for typical photo(electro)chemical
 275 nitrogen fixation processes where yields are typically reported in units of μM
 276 or mM. This large gap between the proximity of efficiency and concentration
 277 targets is due to a combination of large water volumes and the short testing
 278 times that are typically employed for photo(electro)catalysts. Photocatalytic
 279 ammonia production is often measured in the gas-phase, where ammonia
 280 sticks to the catalyst surface and must be washed off with large volumes of
 281 water, leading to low concentrations, and in aqueous photo(electro)chemical
 282 settings the fluid volumes are typically on the order of 100mL while illu-
 283 mination areas are on the order of cm^2 . Furthermore, testing times on the
 284 order of days to weeks are considered long by academic standards. This
 285 leads to extremely low concentrations that are outside of the regime that can
 286 be considered fertilizer. Operating the catalysts in higher ammonia concen-
 287 tration regimes may impact the performance of the process, suggesting that
 288 future efforts should focus on designing cells and testing procedures that lead
 289 to substantially higher concentrations. These higher concentrations lead to
 290 an additional advantage for analytical characterization, since difficulties in
 291 quantifying ammonia at nM - μM concentrations have plagued the field. As
 292 concentration increases the issues with contamination will be less prevalent,
 293 and the presence of ammonia should become unmistakable due to its pungent
 294 odor that can be detected with concentrations as low as 50 ppm (equivalent
 295 to ??? in the aqueous phase).

296 A further consideration that is particularly relevant to electrochemical
 297 ammonia production is the current densities that are required for practical
 298 operation. In the case of solar fuels the overpotential for oxygen evolution
 299 has been defined as the potential at which the current is equal to $10 \text{ mA}/\text{cm}^2$,
 300 equivalent to 10 % solar-to-fuel efficiency. In the case of solar fertilizers the
 301 necessary current will be substantially lower, due to the substantially lower
 302 solar-to-ammonia efficiency requirements. For simplicity, we will assume that
 303 a 0.1% solar-to-ammonia efficiency is required. However, an additional con-
 304 sideration that is more relevant for electrochemical nitrogen fixation is the

Faradaic efficiency that governs the selectivity to ammonia (or nitrates) over other possible products. Indeed, low selectivity to ammonia due to hydrogen evolution has proven to be a critical challenge for electrochemical ammonia synthesis. Typical reported ammonia selectivities are $< 1\%$, although several recent reports have achieved Faradaic efficiencies on the order of 10% . By assuming 10% Faradaic efficiency and an overall solar-to-ammonia efficiency of 0.1% , the relevant current density is 1 mA/cm^2 . Notably, Faradaic efficiency is often a strong function of applied potential (and the resulting current density), with high Faradaic efficiencies typically corresponding to very low current densities on the order of $\text{nA} - \mu\text{A}$. Nonetheless, a recently-reported carbon-based catalyst achieved $>10\%$ Faradaic efficiency at a current density of ca. 4 mA/cm^2 , indicating that it is possible to achieve high Faradaic efficiencies at the proposed operating current of 1 mA/cm^2 . Measuring overpotential and Faradaic efficiencies at practical current densities provides a useful route to identifying electrocatalysts that are promising for solar fertilizer production.

Possible paragraph or table outlining suggested testing standards (temperature, pressure, pH, illumination intensity, etc.) for photo- and electrochemical approaches?

4. Approaches for Solar Capture

The solar fuels community has identified two basic strategies for conversion of solar to chemical energy: direct capture of photons through photochemistry, or indirect capture through photovoltaics coupled to electrochemistry. The hybrid approach of photoelectrochemistry, where electrical bias is applied in conjunction with solar capture has also been explored. There has been considerable debate and analysis regarding the efficacy of these approaches for fuel production (studies by Jaramillo, Lewis, others), and while there is no clear consensus the indirect capture route has received considerable attention. While some of the same considerations apply to the case of solar fertilizers, there are also a number of key differences. In particular, the concentration/efficiency requirements are much lower for fertilizers, and the products are considerably less volatile. While a detailed technoeconomic analysis is beyond the scope of this work, we present some general considerations for each approach.

The direct capture of photons and conversion to fertilizer is the most straightforward and decentralized route to solar fertilizer production. Direct

capture typically involves a single catalytic material (or composite catalyst) that could be produced in massive quantities and distributed to remote locations. It is possible to envision relatively simple reactor designs that could be integrated directly with an irrigation system and not require specialized labor. These systems could be designed without toxic electrolytes, avoiding the need for an additional separation process, and opening the possibility of inexpensive solar fertilizer reactors that could be deployed at the farm scale. However, the concentration of nutrients will be limited by the solar flux, leading to substantial uncertainty and likely lower concentrations. Furthermore, photochemical technologies are relatively untested, and there is currently no catalyst capable of the required solar-to-ammonia efficiency of 0.1 %. The most widely-used photocatalysts are for environmental applications such as reducing contamination or self-cleaning glass where concentrations are low and catalysts are inexpensive. It is possible to envision solar fertilizer schemes that are similar to these environmental applications, but they would likely require close integration with agricultural infrastructure. For example, farms where irrigation is heavily employed are good candidates for direct solar fertilizers, particularly if they are located in remote regions. Roughly 7% of farms in sub-Saharan Africa make use of irrigation. This is far from a majority, but still represents a substantial agricultural footprint where direct photochemical fertilizers might have a practical impact.

The alternative approach of capturing solar energy with photovoltaics and subsequently producing electrochemical ammonia also has a number of advantages. Photovoltaic technology is well-established, and efficiencies of 10-20 % are typical. This leads to a required electrical-to-ammonia efficiency of $\sim 1\%$, which is relatively low and has been reported at the lab scale for state-of-the-art ammonia electrocatalysts. Furthermore, electrochemical technologies have been demonstrated at scale, including the chloroalkali process, water hydrolysis, and hydrogen fuel cells. Electrochemical fertilizer production can be integrated with an electrical grid, providing reliable yields even in periods of no sunlight and the use of high current densities can enable the production of high concentrations of fixed nitrogen. However, large-scale electrochemical processes are far more complex than direct photocatalysis, and would require larger-scale facilities and specialized labor. In addition the practical efficiencies of solar cells on a per-area basis are much lower than their theoretical efficiencies, particularly if they are not installed with advanced technologies such as solar tracking, increasing the capital and labor requirements. Electrochemical processes also require electrolytes, which

379 would likely need to be separated from the effluent and recycled unless non-
380 toxic and inexpensive electrolytes can be identified. These intensive produc-
381 tion processes would lead to more centralized production, and issues with
382 fertilizer transport would become relevant. As centralization increases the
383 process will be in more direct competition with the established Haber-Bosch
384 process, and more detailed technoeconomics are necessary to determine if
385 such an approach is competitive. Nonetheless, the scale of electrochemical
386 processes is still expected to be orders of magnitude below Haber-Bosch, and
387 the process is likely to be less capital-intensive and more robust to uncer-
388 tainty in electrical power. This suggests that agricultural areas near medium
389 or large cities in land-locked areas or developing countries are most promising
390 for indirect capture of solar energy and subsequent electrochemical conver-
391 sion to fertilizers.

392 5. Conclusions

393 Solar fertilizers present an exciting opportunity to directly capture diffuse
394 solar energy and convert it to chemical energy that can be applied at or near
395 the point of production. The technology falls at the complex nexus of energy
396 and agriculture, and substantial additional research is needed to establish
397 the most promising approaches and demonstrate the technology. This work
398 grapples with some initial considerations from the perspective of agronomics
399 and photoelectrochemistry, and identifies some preliminary metrics that will
400 aid in the development and deployment of solar fertilizer technologies. Spe-
401 cific metrics are presented to identify the target solar-to-ammonia efficiency
402 (0.1%), minimum nitrogen concentration (1 wt%), and electrochemical cur-
403 rent density (1 mA/cm²) that may enable solar fertilizer technology, and
404 considerations for assessing direct and indirect capture and conversion of so-
405 lar energy are presented. The metrics and considerations presented draw on
406 a range of expertise in the diverse fields of agronomics, photoelectrocataly-
407 sis, and process systems engineering, and provide a starting point for further
408 development of solar fertilizer technologies. There are many possible routes
409 forward for this nascent field, and identifying the most promising will require
410 a diverse range of technical, social, and economic considerations. However,
411 the vast potential impact of solar fertilizers on the growing problem of world
412 hunger makes this challenging endeavor worthwhile.