Carbon emission avoidance and capture by producing in-reactor microbial biomass based food, feed and slow release fertilizer: potentials and limitations

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Abstract

To adhere to the Paris Agreement of 2015, we need to store several gigatonnes (Gt) of carbon annually. In the last years, a variety of technologies capture carbon and storage (CCS) and capture carbon and usage (CCU) have been demonstrated. While conventional CCS and CCU are techno-economically feasible, their climate change mitigation potentials are limited, due to limited amount of CO₂ that can be captured. Hence, there is an urgent need to explore other CCS and CCU routes. Here, we discuss an interesting alternative route to capture carbon dioxide from industrial point sources, using microbial biomass through autotrophic oxidizing micro-organisms. The produced microbial biomass is often referred to as microbial protein (MP) because it has a crude protein content of ~70- 75%. Depending on the industrial production process and final quality of the produced MP, it can be used for human consumption as meat replacement, protein supplement in animal diets as an alternative for soy and fish meal, or slow release organic fertilizer providing both organic nitrogen as carbon to agricultural soils. Here, we discuss the potentials and limitations of this so far unexplored CCU approach and provide a preliminary assessment of the economic feasibility of the different routes for CO₂ carbon reduction, capture and utilization routes.

38 **The need for and limitations of carbon capture and utilization methods**

39 To meet the climate change mitigation challenge and adhere to the Paris Agreement of 2015, we need
40 to store about 4-5 Gigatonnes (Gt) CO₂ per year [1]. Several technologies for capture carbon and
41 storage (CCS) and capture carbon and usage (CCU) exist and their technological feasibility has been
42 demonstrated [1]. Underground storage of CO₂ gas is the cheapest option [2], but beyond climate
43 change abatement, this approach brings about no net benefits.

44 While conventional methods of CCS and CCU are techno-economically feasible, their overall
45 potential in terms of global climate change abatement is limited [1]. For example, the expectation of
46 CO₂ injection into geological reservoirs to achieve enhanced oil recovery (EOR-CCS), at the current
47 prices of oil and of CO₂, at best only cover 4-8% of the mitigation challenge by 2050 [1]. The economic
48 feasibility is directly linked to the oil price, so with highly variable oil prices, the economics of storage
49 by the oil industry also becomes less attractive. Another route is the use of carbon dioxide as a
50 feedstock to produce chemicals [3, 4]. The two chemicals which really represent major CO₂ capture
51 potential at present are urea (*i.e.*, 132 Mt CO₂ equivalent per year) and methanol (*i.e.*, 10 Mt CO₂
52 equivalent per year) [4]. Also other bulk chemicals that be produced through electrosynthesis from
53 CO₂, such as acetate and butyrate, in the framework of the “electrifying of the economy” concept are
54 generated through direct CCU . However, the entire CO₂-to-chemical route can, at best, account for
55 1% of required carbon storage, and will most likely not play a major role in climate change mitigation
56 in the years ahead [1], although it could provide a fossil-fuel independent source of chemicals. Hence,
57 although these different CCS and CCU techniques allow efficient and economically feasible carbon
58 capture, their ability to reduce current CO₂ emission levels is, at present, insufficient.

59 Considering the limitations of the available methods, and the urgency to deal with climate
60 change, there is a need to explore other routes that can (1) effectively avoid carbon emissions, (2)
61 capture and utilize carbon, and (3) offer the possibility of being implemented in the near future. First,
62 such alternative routes must have a clear-cut positive impact on the global economy, the environment
63 and public health. An interesting alternative option that, so far, has not been explored on industrial

scale, is carbon capture coupled with storage in and utilization as microbial biomass by using autotrophic micro-organisms that rely on renewable hydrogen, the so-called hydrogen oxidizing bacteria (HOB) (Figure 1) [5, 6].

Fig 1. Overall scheme of the production of microbial protein from Haber-Bosch nitrogen, CO₂ and H₂ and O₂ driven by renewable energy.

The autotrophic microbial biomass can, depending on the industrial production process and final quality of the microbial biomass, be used for (1) human food as a protein source (as a meat substitute), (2) protein rich feed for livestock and (3) slow-release organic fertilizer providing both nutrients to the crops, but also serving as a means for long-term carbon storage in agricultural soils [7-12]. In all three cases, the microbial based biomass represents a temporary storage, but this approach integrates possibilities to decrease the demand for fossil fuel through direct CO₂ usage by the autotrophic HOB. In this paper, we highlight the potential and limitations of such an approach, and we provide a rough assessment of the economic feasibility of the different routes for CO₂ carbon reduction, capture and utilization routes.

Carbon capture potential and its economics

82 Independent of the different end-use possibilities described above, the factor determining the
83 practical feasibility of the carbon capture and storage potential, is the availability of CO₂ that can be
84 captured at large scale from industrial point sources at economically competitive costs. Examples of
85 such industrial sites involve household waste incinerators, steel plants and anaerobic digestion plants.
86 The advantage of using CO₂ from the anaerobic digester combined heat and power unit for MP
87 production lies in the fact that it can provide (1) renewable electricity for H₂ production, and (2) CH₄
88 that can be used directly as carbon and energy source, thus, surpassing the need for energetic losses
89 of CH₄ conversion to electricity. Assessments by the Intergovernmental Panel on Climate Change (IPCC)
90 have revealed that already in 2020, the annual amount CO₂ that can be captured at economically
91 feasible costs from industrial point sources will reach 0.7 - 1.3 GtC/year (2.6 to 4.9 Gt CO₂/year) [13].
92 This is already in the same order as the amount of carbon, *i.e.*, 4-5 Gt/year that needs to be stored. By
93 2050, the carbon capture potential is estimated to reach 1.3–10 Gt C/year, which reflects 4.7 - 37.5 Gt
94 CO₂/year.

95 The production costs of hydrogen-based microbial protein are estimated at US\$2800 per tonne
96 product (*i.e.*, dry microbial based biomass at a crude protein content of 70-75%) [14]. The hydrogen
97 production costs by means of water electrolysis comprise about 60% of the total production costs for
98 hydrogen based microbial protein [14]. These estimated costs are based on a cost of hydrogen of \$3/kg
99 hydrogen through water electrolysis using renewable energy as the energy source at a unit price of
100 \$0.05 per kWh. In recent years, considerable progress has been made in renewable energy generation,
101 with costs for large scale electricity generation using large scale-solar photovoltaics, with recent bids
102 already reaching prices as low as US\$0.03 per kWh generated [15].

103

104 **The different levels of microbial protein: from direct food to slow-release fertilizer application**

105 **3. Microbial protein for human consumption as a meat substitute**

106 Microbial protein (MP) as a food product suitable for human consumption is not new, with
107 microorganisms in the form of fungi, yeast, bacteria and algae being used in food processing for human

consumption (e.g., bread, yoghurt, mushrooms and beer) for several hundred years [16, 17]. In recent years, there has been an increasing interest in MP for human consumption as a meat substitute. The MP can already be produced at commercially competitive prices, and is increasingly sold as meat substitutes in fungal based MP products, like Quorn^(TM). A more challenging issue is to opt for MP produced not from carbohydrates (as in the case for Quorn^(TM)), but from non-food CO₂ as a carbon source, coupled with hydrogen as an energy source (Figure 1). Interestingly, the concept of using carbon dioxide and hydrogen to produce MP food is not completely new. Human trials were already conducted by NASA in the 1960s in their quest to produce food for astronauts [18]. The production of *Spirulina platensis* in the MELiSSA loop is an excellent example of how integrated nutrient recovery in space can be used to produce MP.

Considering production costs of about \$2800/tonne (dry microbial based biomass at a crude protein content of 70-75%), and the current value of top-quality protein for human food in the market (such as, for instance, pea protein) of about US\$3500-5000/tonne, it appears that the capture and upgrading of CO₂ to microbial protein has reached a stage of economic feasibility. However, when looking at absolute values, carbohydrate-based products like Quorn^(TM), although increasing in produced volumes, at present, represent only a very small fraction of the overall protein market with an annual production of 25,000 tonnes per year [17]. A comparison of the CO₂ footprint of N-fixing crops, such as soy, reveals that it amounts 4-8 tonnes of CO₂ equivalents per tonne soy dry matter produced [19]. In contrast, the microbial route has, in principle, a CO₂ footprint that is negative, since anthropogenic CO₂ is fixed, and the microbial biomass produced is generated through green energy, and can be harvested and dried in an energy neutral way, by using natural drying processes. Hence, if the concept of hydrogen oxidizing bacteria based food production could be implemented, it offers the potential to contribute to CO₂ reduction relative to the conventional agro-supply line. Despite the enormous market potential to feed 7.5 billion people worldwide with nutritious microbial protein, it seems unlikely that this microbial-based carbon capture and utilization route will directly influence climate change. This is related to the fact that consumers would need to adapt rapidly in the near

134 future to this unusual food supply, provided also that it qualifies under the rigorous demands imposed
135 by the regulator on novel foods. However, as the market is currently already open to microbial
136 products, such as Quorn^(TM), *Spirulina*, and other less obvious microbial products, such as cheese and
137 beer, the legislative and societal acceptance could fall within this framework, making the transition to
138 MP less troublesome. The onset of such a route in coming decades has the potential to reduce the
139 pressure on agricultural land [5], one of the key drivers of deforestation, biodiversity loss and land use
140 change induced greenhouse gas emissions [20-23].

141

142 **2. Microbial based biomass for protein rich animal feed**

143 The production of MP to produce livestock feed is well documented [16, 24]. It was already produced
144 at industrial scale in the 1970s [5, 17], when MP was often referred to as single cell protein (SCP). In
145 1976, the UNESCO science price was awarded to 'large-scale and low-cost production of single cell
146 proteins from oil' [25]. The bacterial protein product, called Pruteen[®], produced from methanol, was
147 commercialized by Imperial Chemical Industries Ltd in 1980. Interestingly, the Soviet Union
148 government was very active in achieving large-scale industrial production of microbial protein. As
149 described in a recent de-classified CIA report, the Soviet Union had a state-wide research programme,
150 entitled "The Soviet Hydrocarbon-Based Single Cell Protein Program", aiming to produce microbial
151 protein in the form of yeast using n-paraffin derived from oil as the carbon and energy source [26].
152 Despite these major international efforts, MP never reached full market potential with most of these
153 initiatives being ceased at the end of the 1980s.

154 In recent years, the production of MP has regained significant interest, particularly in the
155 aquaculture industry, with the production of natural gas based MP as a fish food, reaching industrial
156 production at economically competitive prices [27]. The fact that this process relies heavily on the use
157 of natural gas implies that such a pathway will not provide an ultimate long-term sustainable solution.
158 Recently, it was demonstrated that high-quality MP with an amino-acid composition similar to fish
159 meal can be produced using hydrogen as energy source coupled with carbon capture [6]. Currently,

MP production costs appear to be substantially higher than conventional protein rich supplements, like soy bean meal and fish meal, with market prices in the last 5 years in the order of US\$600-1100 per ton for soy bean meal and \$2000-3000 per ton for fish meal, both expressed as 100% protein crude content [28]. Clearly, the hydrogen based MP production route cannot yet compete with the soybean-for-feed route. It could be competitive with fish protein, though its demand will certainly remain high, due to its very valuable amino acid profile. Current practice of supplying aquaculture with wild-catch fish protein harvested from the ocean, however, is subject to severe environmental considerations, which creates possibilities for other more sustainable opportunities, such as MP. The global aquaculture industry is, at present, under enormous pressure to find alternative, more sustainable, protein sources. An example of such an approach is the biofloc technology for combined carbon and nitrogen balancing and *in situ* feed production. Microbial protein production, driven by renewable energy, and coupled with carbon capture, could be an interesting ‘out of the box’ solution that warrants further exploration.

173

1. Production of Microbial Based slow release Organic Nitrogen (MBB-SON) fertilizer for soil carbon sequestration

Enhancing the soil organic carbon content improves the soil homeostasis and resistance against physical and chemical disturbance, and is well known to increase crop yields [29-35]. The increase in soil organic carbon also enhances the water holding capacity [36, 37], cation exchange capacity and aggregation, and reduces the occurrence of soil erosion [30]. Recently, increasing the soil carbon of agricultural soils has been proposed as a climate change mitigation tool. The global carbon currently stored in soils is about a factor 3.3 higher than the CO₂ levels in our atmosphere [9]. In 2015, the ‘4 per mille Soils for Food Security and Climate’ [38] was launched at the COP21 in Paris, with the aspirational goal to increase global soil organic matter stocks by 0.4 % per year, which could make a strong contribution to reducing atmospheric CO₂ concentrations [39]. Agricultural soils are of particular interest because these soils have been substantially depleted in soil organic carbon since the

186 introduction of intensive agricultural practices, so these have the highest potential to increase in
187 carbon content [8]. If the 0.4% increase were restricted to agricultural soils, the carbon sequestration
188 potential would be around 1.2 GtC/ year, which corresponds to about 4-5 Gt CO₂ per year [40], and
189 this should, in theory, be sufficient to comply with Paris Agreement targets, if immediate and
190 aggressive mitigation is pursued. However, considering an average C/N ratio of 12 for soil organic
191 carbon (SOC) [41], this would require some 100 Teragram reactive nitrogen per year. This value
192 corresponds with the yearly supply of nitrogen from the entire global fertilizer industry [42]. Hence,
193 achieving the CO₂ mitigating challenge in which the soils play an important role seems unlikely, with
194 the availability of reactive nitrogen being the limiting factor. It can be suggested to focus on 'over-
195 exploited' soils, and try to return them to agricultural practices that assure that the soil organic carbon
196 is not decreasing, and at least remains constant. This will not only prevent increasing soil-related CO₂
197 emissions, it will also sustain overall physico-chemical stability of the soil, with higher biomass yields.

198 The addition of organic materials, such as compost, peat, sewage sludge, and manure, to
199 increase soil organic carbon levels and enhance crop yield are well-established methods [31]. The use
200 of compost and sewage sludge is often impaired by the fact that these can contain heavy metals and
201 organic pollutants arising from pesticides, pharmaceuticals and personal care products [43-46]. Animal
202 manure is largely free from such pollutants, but there is increasing concern that manure addition could
203 result in agricultural soils that accumulate antibiotic resistant bacteria [43, 44, 47-50]. Even following
204 anaerobic digestion, several antibiotics, such as monensin, present in for example swine manure, are not
205 removed, and subsequent application to the soil will result in spreading antibiotics an antibiotic resistance
206 genes. Moreover, their overall potential in terms of climate change mitigation is limited [51]. Considering
207 the above-mentioned stoichiometric constraints in terms of nutrient, especially nitrogen, availability, and
208 limitations of conventional methods to increase carbon content of soils in the context of climate mitigation,
209 we suggest to use a novel approach in which MP is used as a slow-release organic nitrogen fertilizer (Figure
210 1). The production process is almost identical to the MP based food and feed production processes
211 described in the sections above, but with some key differences in process requirements. The fermentation

212 conditions are less strict in terms of hygiene, there is no need for sterilization and consistent
213 composition of the microbial biomass (*i.e.*, no need for strict, pure culture conditions), and the final
214 product does not require a 100% dry form, reducing the drying requirements.

215 The production of this MP for slow-release nitrogen supply to the soil would still rely on the use of
216 Haber-Bosch process to produce the reactive nitrogen source (Figure 1). However, the inorganic Haber-
217 Bosch nitrogen fertilizer is transformed into an organic nitrogen form, which has a higher long-term
218 stability. The rationale behind this is that, worldwide, inorganic nitrogen fertilizer has a very low use-
219 efficiency of 40%, due to leaching, run-off, denitrification and volatilization [42]. The concept is that
220 upgrading this mineral nitrogen to organic nitrogen in the form of MP increases the nitrogen use
221 efficiency with concomitant enrichment of the agricultural soil with organic matter. While many
222 studies highlight the positive impact of increasing the soil organic carbon on *e.g.*, agricultural yields,
223 carbon storage, nutrient and water retention as highlighted above, greenhouse gas fluxes from
224 agricultural soils are complex and highly heterogeneous [52-54]. Under certain soil conditions, the
225 increase in soil organic carbon and organic nitrogen levels could even increase carbon dioxide,
226 methane and nitrogen emissions from the soil. The availability and spreading of O₂ in the soil will be a
227 crucial to avoid nitrogen losses due to complete (N₂) or incomplete (N₂O) denitrification, and CH₄ losses
228 due to anaerobic sites. As both N₂O and CH₄ have a 100-year global warming potential that is a factor
229 265 and 28, respectively higher than CO₂, their emission from the soil should be avoided at all cost.
230 Long-term trials would be essential to verify whether the addition of MP results in increased storage
231 of carbon in the soil organic matrix, coupled with low nitrogen and highly potent greenhouse gas
232 emissions.

233 A situation can be considered in which the total current global use of Haber-Bosch fertilizer N
234 of ~100 Mt/year [55] would first be upgraded to MP. Considering a typical C/N ratio for microbial
235 biomass of 5 [5], the theoretical potential of MP to capture and temporarily store carbon in the soils
236 reaches 0.5 Gt C/year (1.83 Gt CO₂/year). This is substantially lower than the amount of carbon that
237 has to be sequestered per annum in soils according to the Paris mitigation challenges (*i.e.*, 1.2 Gt C)

238 [39]. Part of this MP carbon will be released from the soils over time, as it is biodegraded to release
239 nitrogen to the plants, thus, decreasing the net carbon captured. Nonetheless, given its potential to
240 capture CO₂, the overall potential of MP remains high and relevant in the framework of climate change
241 abatement.

242 In addition to the limitations in carbon capture potential, this approach also comes with
243 considerable economic constraints. Considering the production cost of about 2800 US\$/tonne HOB-
244 based MP, which is equivalent to a cost of ~US\$1500/tCO₂ incorporated, it is clear that these values
245 are much higher than the economic costs for underground carbon storage of CO₂ or other available
246 CCU routes [2]. In contrast to the production of MP as human food or animal feed, where the microbial
247 biomass product has a high market value, MP for soil application has to compete with alternative
248 organic nitrogen fertilizers, such as (digested) manure, sludge, kelp, feathers, blood and horn meal, as
249 well as with inorganic fertilizer. These have a relatively low market value, especially inorganic
250 fertilizers, with prices for urea below US\$500/t N [56]. The use of inorganic nitrogen is integrated in
251 the MP production cost at a value of US\$112/tonne MP, which is only a fraction of the overall
252 production cost (4%). Even when considering high carbon pricing schemes of US\$150–220/t CO₂ when
253 implementing low stabilisation climate targets such as the Representative Concentration Pathways
254 (RCPs) [57], at best, a carbon capture benefit of about US\$ 400/tonne MP can be achieved. Even under
255 these low stabilization climate targets, the organic nitrogen has a cost of US\$2280 per 160 kg N present
256 in the MP, which is equivalent to 14000 US\$/tonne organic N. This is a factor 10 - 20 higher than the
257 current commodity prices for inorganic and organic nitrogen.

258 In addition to the economic limitations describe above, there are also substantial energy-
259 related constraints. The production of MP for soil application requires substantial amounts of
260 renewable energy to produce hydrogen *via* water electrolysis. It would require 3000 Gigawatt of
261 renewable energy per Gt of MP produced [14]. To put this amount into a global context; the current
262 installed capacity of renewables worldwide is only 912 Gigawatt [58]. Hence, the application of MP as
263 carbon and nitrogen source to improve soil homeostasis and stability appears to be promising, but (1)

the CO₂ emission reduction is too limited, (2) the risk to release other more potent greenhouse gasses too high, and (3) the economic picture too unfavourable to evolve towards short-term sustainable applications.

Conclusions

To deal with the climate change challenge, there is an urgent need to develop alternative routes that can be implemented in the near future, capable of effectively reducing carbon emissions and/or capturing and utilizing carbon, that also have a positive impact on the environment and the global economy. Here, we examined the potential of autotrophic hydrogen oxidizing bacteria to capture and utilize carbon in the form of human food, protein rich animal feed and slow release nitrogen fertilizer. The production of food *via* the route of microbial protein has the current potential to decrease the use of fossil fuel, water, pesticides, and land use, to provide the global population with nutritious protein, but there may be issues with public acceptability/demand and further research concerning its composition and potential side effects is required. The production of microbial protein as animal feed *via* autotrophic microbial biomass is not yet economically competitive. At current hydrogen production costs through water electrolysis, the overall production price of microbial protein exceeds the costs of conventional soybean and fishmeal. However, if in the future or in specific geographic regions the cost can be decreased substantially or the as costs of conventional soybean and fishmeal increase, this line of production of protein could become cost competitive.

The production of microbial protein for slow-release organic nitrogen fertilizer applications is clearly of interest to considerably increase the carbon content in agricultural soils, and in light of its potential to reduce global nitrogen pollution. The dynamics of such an increase in soil organic carbon storage through this route are hard to predict and would be reversible. Despite its theoretical potential as a clean-tech solution to capture carbon and increase soil organic carbon content, the current low market value of organic nitrogen fertilizer, the high-energy demands and current production costs, severely limits the practical feasibility and potential as a climate change mitigation tool. Although

290 microbial protein does not seem immediately ready for practice, this concept opens new long-term
291 perspectives to serve as a food and feed source, combined with its potential to contribute to carbon
292 capture and climate change abatement.

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