

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

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21

22 **Abstract**

23 To adhere to the Paris Agreement of 2015, we need to store several gigatonnes (Gt) of carbon
24 annually. In the last years, a variety of technologies for carbon capture and storage (CCS) and
25 carbon capture and usage (CCU) have been demonstrated. While conventional CCS and CCU
26 are techno-economically feasible, their climate change mitigation potentials are limited, due to
27 limited amount of CO₂ that can be captured. Hence, there is an urgent need to explore other
28 CCS and CCU routes. Here we discuss an interesting alternative route for capture of carbon
29 dioxide from industrial point sources, using CO₂-binding, so-called autotrophic aerobic bacteria
30 to produce microbial biomass as a C-storage product. The produced microbial biomass is often
31 referred to as microbial protein (MP) because it has a crude protein content of ~70- 75%.
32 Depending on the industrial production process and final quality of the produced MP, it can be
33 used for human consumption as meat replacement, protein supplement in animal diets, or slow-
34 release organic fertilizer thus providing both organic nitrogen and carbon to agricultural soils.
35 Here, we discuss the potentials and limitations of this so far unexplored CCU approach. A
36 preliminary assessment of the economic feasibility of the different routes for CO₂ carbon
37 avoidance, capture and utilization indicates that the value chain to food is becoming attractive
38 and that the other end-points warrant close monitoring over the coming years.

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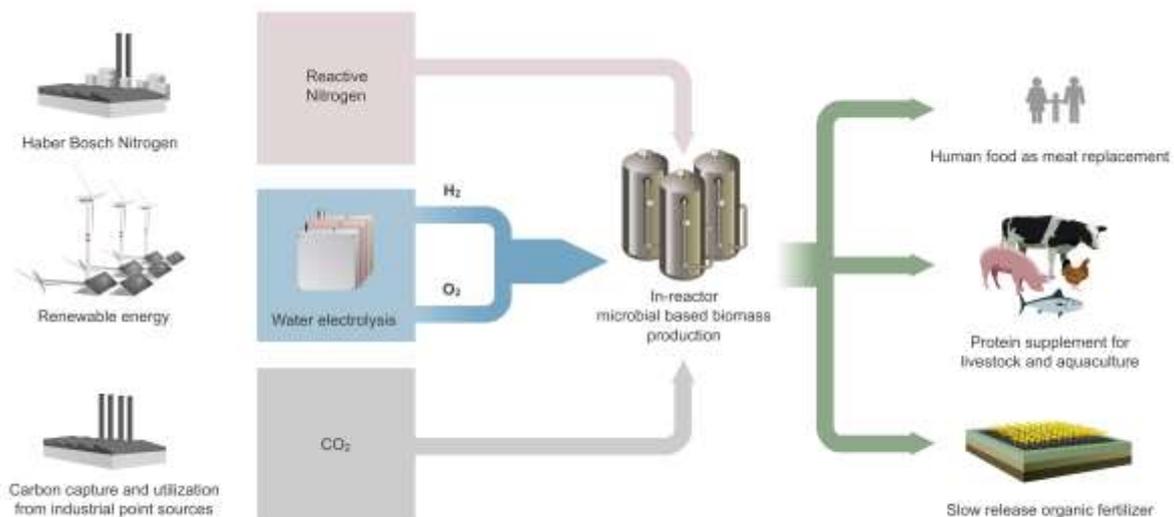
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42 **The need for and limitations of carbon capture and utilization methods**

43 To meet the climate change mitigation challenge and adhere to the Paris Agreement of 2015,
44 we need to store about 4-5 Gigatonnes (Gt) CO₂ per year (Mac Dowell et al. 2017). Several
45 technologies for carbon capture and storage (CCS) and carbon capture and usage (CCU) exist
46 and their technological feasibility has been demonstrated (Mac Dowell et al. 2017).
47 Underground storage of CO₂ gas is the cheapest option (Service 2016), but beyond climate
48 change abatement, this approach brings about no net benefits.

49 While conventional methods of CCS and CCU are techno-economically feasible, their
50 overall potential in terms of climate change mitigation is limited (Mac Dowell et al. 2017). For
51 example, the expectation of CO₂ injection into geological reservoirs to achieve enhanced oil
52 recovery (EOR-CCS), at the current prices of oil and of CO₂, at best only cover 4-8% of the
53 mitigation challenge by 2050 (Mac Dowell et al. 2017). The economic feasibility is directly
54 linked to the oil price, so with **low** oil prices, the economics of storage by the oil industry also
55 becomes less attractive. Another route is the use of carbon dioxide as a feedstock to produce
56 chemicals (Aresta et al. 2013, Martens et al. 2017). The two chemicals which really represent
57 major CO₂ capture potential at present are urea (*i.e.*, 132 Mt CO₂ equivalent per year) through
58 an 2-step chemical process in which CO₂ first undergoes an exothermic reaction with liquid
59 ammonia to form (NH₄)₂CO₃ followed by endothermic decomposition and dehydration of
60 (NH₄)₂CO₃ into urea and methanol (*i.e.*, 10 Mt CO₂ equivalent per year) *via* catalytic
61 hydrogenation of CO₂ (Aresta et al. 2013, Boot-Handford et al. 2014). However, the entire CO₂-
62 to-chemical route can, at best, account for about 1% of required carbon storage, and will most
63 likely not play a major role in climate change mitigation in the years ahead (Mac Dowell et al.
64 2017). Hence, although these different CCS and CCU techniques allow efficient and
65 economically feasible carbon capture, their ability to decrease current CO₂ emission levels is,
66 at present, insufficient.

67 Considering the limitations of the available methods, and the urgency to deal with climate
68 change, there is a need to explore other routes that can (1) effectively avoid carbon emissions,
69 (2) capture and utilize carbon, and (3) offer the possibility of being implemented in the near
70 future. Obviously, such alternative routes must have a clear-cut positive impact on the global
71 economy, the environment and public health. An interesting alternative option that, so far, has
72 not been explored on industrial scale, is carbon capture coupled with storage in and utilization
73 as microbial biomass by using autotrophic micro-organisms that rely on renewable hydrogen,
74 the so-called hydrogen oxidizing bacteria (HOB) (Figure 1) (Matassa et al. 2015, Matassa et al.
75 2016b, Pikaar et al. 2017a). The key feature of these bacteria is that they have a special capacity
76 to use the energy which becomes available when they enzymatically combine hydrogen gas
77 with oxygen gas to produce water; the renewable energy initially invested to electrolyse the
78 water to hydrogen and oxygen is thus recovered by the bacteria and used to build up CO₂ and
79 minerals into their cellular components.
80



81
82 **Fig 1. Overall scheme of the production of Microbial Based Biomass from Haber-Bosch**
83 **nitrogen, CO₂ and H₂ and O₂ driven by renewable energy.**
84

85 The autotrophic microbial biomass that is formed from CO₂ under aerobic conditions
86 can, depending on the industrial production process and final quality of the microbial biomass,
87 be used for (1) human food as a protein source (as a meat substitute), (2) protein rich feed for
88 livestock and (3) slow-release organic fertilizer providing both nutrients to the crops, but also
89 serving as a means to store carbon in agricultural soils (Lal 2004a, b, 2008, Paustian et al. 1997,
90 Paustian et al. 2016, Smith 2016). Clearly, in all three cases, the microbial based biomass
91 represents a temporary storage, but this approach integrates possibilities to decrease the demand
92 for fossil fuel through direct CO₂ usage by the autotrophic HOB. In this paper, we highlight the
93 potential and limitations of such an approach, and we assess the economic feasibility of the
94 different routes for CO₂ carbon avoidance, capture and utilization routes.

95

96 **Carbon capture potential and its economics**

97 Independent of the different end-use possibilities described above, the factor determining the
98 practical feasibility of the carbon capture and storage potential, is the availability of CO₂ that
99 can be captured and upgraded to adequate quality at large scale from industrial point sources
100 (e.g. incinerators, cement ovens and steel plants) or could even be transformed into syngas at
101 economically competitive costs (Boot-Handford et al. 2014, Verbeeck et al. 2018). Assessments
102 by the Intergovernmental Panel on Climate Change (IPCC) have revealed that already in 2020,
103 the annual amount CO₂ that can be captured at economically feasible costs from industrial point
104 sources will reach 0.7 - 1.3 Gt C/year (2.6 to 4.9 Gt CO₂/year) (IPCC 2005). This is already in
105 the same order as the amount of carbon, *i.e.*, 4-5 Gt/year that needs to be stored. By 2050, the
106 carbon capture potential is estimated to reach 1.3–10 Gt C/year, which reflects 4.7 - 37.5 Gt
107 CO₂/year.

108 The production costs of hydrogen-based microbial protein are estimated at US\$2800 per
109 tonne product (*i.e.*, dry microbial based biomass at a crude protein content of 70-75%) (Pikaar

110 et al. 2018). The hydrogen production costs by means of water electrolysis comprise about 60%
111 of the total production costs for hydrogen based microbial protein (Pikaar et al. 2018). These
112 estimated costs are based on a cost of hydrogen of \$3/kg hydrogen through water electrolysis
113 using renewable energy as the energy source at a unit price of \$0.05 per kWh. In recent years,
114 considerable progress has been made in renewable energy generation, with costs for large scale
115 electricity generation using large scale-solar photovoltaics, with recent bids already reaching
116 prices as low as US\$0.03 per kWh generated (Haegel et al. 2017).

117

118 **Microbial protein for human consumption as a meat substitute**

119 Microbial protein (MP) as a food product suitable for human consumption is not new with
120 microorganisms in the form of fungi, yeast, bacteria and algae being used in food processing
121 for human consumption (*e.g.*, bread, yoghurt, mushrooms and beer) for thousands of years
122 (Anupama and Ravindra 2000, Matassa et al. 2016a). In recent years, there has been an
123 increasing interest in MP for human consumption as a meat substitute. Indeed, MP can already
124 be produced at commercially competitive prices, and is increasingly sold as meat substituents
125 in fungal based MP products, like Quorn^(TM). Yet, a more challenging issue is to opt for MP
126 produced not from carbohydrates (as in the case for Quorn^(TM)), but from non-food CO₂ as a
127 carbon source, coupled with hydrogen as an energy source (Figure 1). Interestingly, the concept
128 of using carbon dioxide and hydrogen to produce MP food is not completely new. Human trials
129 were already conducted by NASA in the 1960s in their quest to produce food for astronauts
130 (Waslien et al. 1969). The production of *Spirulina platensis* in the MELiSSA loop is an
131 excellent example of how integrated nutrient recovery in space can be used to produce MP
132 (Gòdia et al. 2002).

133 Considering total production costs of about \$2800/tonne (dry microbial based biomass
134 at a crude protein content of 70-75%; all costs in terms of ingredients, mixing, pumping,

135 dewatering, drying, sterilization, processing, overhead, and CAPEX) (Pikaar et al. 2018), and
136 the current value of top-quality protein for human food in the market (such as, for instance, pea
137 protein) of about US\$3500-5000/tonne, it appears that the capture and upgrading of CO₂ to
138 microbial protein has reached a stage of economic feasibility. However, when looking at
139 absolute values, carbohydrate-based products like Quorn^(TM), although increasing in produced
140 volumes, at present, represent only a very small fraction of the overall protein market with an
141 annual production of 25,000 tonnes per year (Matassa et al. 2016a). A comparison of the CO₂
142 footprint of N-fixing crops, such as soy, reveals that it amounts 4-8 tonnes of CO₂ equivalents
143 per tonne soy dry matter produced (<http://faostat.fao.org/>). In contrast, the microbial route has,
144 in principle, a CO₂ footprint that is negative, since anthropogenic CO₂ is fixed, and the
145 microbial biomass produced is generated through green energy, and can be harvested and dried
146 in an energy neutral way, by using natural drying processes. Hence, if the concept of hydrogen-
147 oxidizing bacteria based food production could be implemented, it offers the potential to
148 contribute to CO₂ avoidance relative to the conventional agro-supply line. Despite the enormous
149 market potential to feed 7.5 billion people worldwide with nutritious microbial protein, it seems
150 unlikely that this microbial-based carbon capture and utilization route will directly influence
151 climate change. This is related to the fact that consumers would need to adapt rapidly in the
152 near future to this unusual food supply, provided also that it qualifies under the rigorous
153 demands imposed by the regulator on novel foods. However, as the market is currently already
154 open to microbial products, such as Quorn^(TM), *Spirulina*, and other less obvious microbial
155 products, such as cheese and beer, the legislative and societal acceptance could fall within this
156 framework, making the transition to MP less troublesome. The onset of such a route in the
157 coming decades has the potential to decrease the pressure on agricultural land with some 9%
158 (Pikaar et al. 2017a), one of the key drivers of deforestation, biodiversity loss and land use

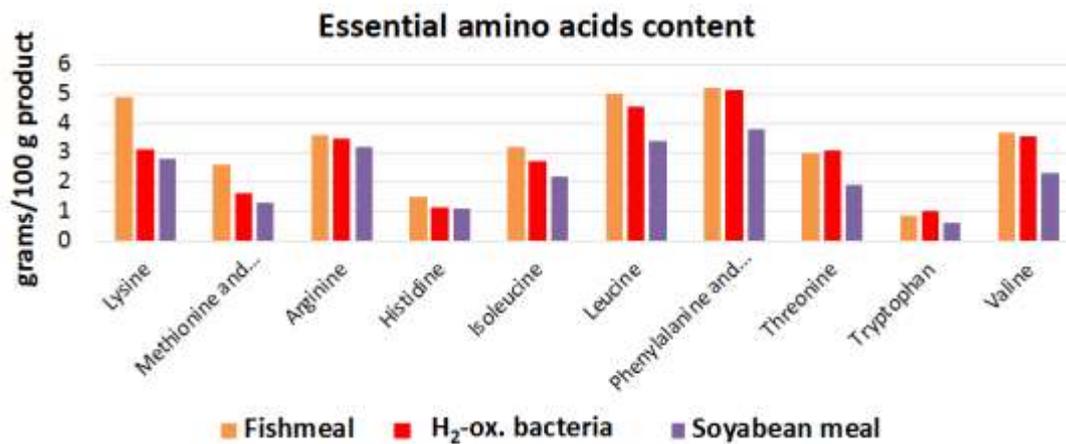
159 change induced greenhouse gas emissions (Crist et al. 2017, Maxwell et al. 2016, Newbold et
160 al. 2015, Popp et al. 2014).

161

162 **Microbial based biomass for protein rich animal feed**

163 The production of MP to produce livestock feed is well documented (Anupama and Ravindra
164 2000, Kihlberg 1972). It was already produced at industrial scale in the 1970s (Matassa et al.
165 2016a, Pikaar et al. 2017a), when MP was often referred to as single cell protein (SCP). In 1976,
166 the UNESCO science price was awarded to ‘large-scale and low-cost production of single cell
167 proteins from oil’ (Pikaar et al. 2017b). The bacterial protein product, called Pruteen[®], produced
168 from methanol, was commercialized by Imperial Chemical Industries Ltd in 1980.
169 Interestingly, the Soviet Union government was very active in achieving large-scale industrial
170 production of microbial protein. As described in a recent de-classified CIA report, the Soviet
171 Union had a state-wide research programme, entitled “The Soviet Hydrocarbon-Based Single
172 Cell Protein Program”, aiming to produce microbial protein in the form of yeast using n-paraffin
173 derived from oil as the carbon and energy source (CIA 1977). Despite these major international
174 efforts, MP never reached full market potential with most of these initiatives being ceased at
175 the end of the 1980s.

176 In recent years, the production of MP has regained significant interest, particularly in
177 the aquaculture industry, with the production of natural gas based MP as a fish food, reaching
178 industrial production at economically competitive prices (<http://calystanutrition.com/>). The fact
179 that this process relies heavily on the use of natural gas implies that such a pathway will not
180 provide an ultimate long-term sustainable solution. Recently, it was demonstrated that high-
181 quality MP with an amino-acid composition similar to fish meal can be produced using
182 hydrogen as energy source coupled with carbon capture (Matassa et al. 2016b) (see Fig 2).



183

184 **Figure 2. Comparison of essential amino acid composition of H₂-oxidizing microbial**
 185 **protein by a *Sulfuricurvum spp.* dominated culture (red) with fish meal (orange) and soy**
 186 **bean meal (purple), adapted from Mattasa et al., (2016) (Matassa et al. 2016b).**

187

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

200

201 **Production of Microbial Based slow release Organic Nitrogen (MBB-SON) fertilizer for**
 202 **soil carbon sequestration**

203 It is widely accepted that enhancing the soil organic carbon content in general improves the soil
204 health and is well known to increase crop yields (Diacono and Montemurro 2010, Lal 2006,
205 2009, 2010, 2011, Lal et al. 2007, Steiner et al. 2007). The increase in soil organic carbon also
206 enhances the water holding capacity (Emerson 1995, Rawls et al. 2003), cation exchange
207 capacity and aggregation, and reduces the occurrence of soil erosion (Lal 2006). Recently,
208 increasing the soil carbon of agricultural soils has been proposed as a climate change mitigation
209 tool (Minasny et al. 2017). Indeed, the global carbon currently stored in soils is about a factor
210 3.3 higher than the CO₂ levels in our atmosphere (Lal 2004a). In 2015, the ‘4 per mille Soils
211 for Food Security and Climate’ (<http://4p1000.org/>) was launched at the COP21 in Paris, with
212 the aspirational goal to increase global soil organic matter stocks by 0.4 % per year, which
213 could make a strong contribution to decreasing atmospheric CO₂ concentrations (Minasny et
214 al. 2017). Agricultural soils are of particular interest because these soils have been substantially
215 depleted in soil organic carbon since the introduction of intensive agricultural practices, so these
216 have the highest potential to increase in carbon content (Lal 2004b). If the 0.4% increase were
217 restricted to agricultural soils, the carbon sequestration potential would be around 1.2 GtC/ year,
218 which corresponds to about 4-5 Gt CO₂ per year (van Groenigen et al. 2017), and this should,
219 in theory, be sufficient to comply with Paris Agreement targets, if immediate and aggressive
220 mitigation is pursued. However, considering an average C/N ratio of 12 for soil organic carbon
221 (SOC) (Batjes 1996), this would require some 100 Teragram reactive nitrogen per year. This
222 value corresponds with the yearly supply of nitrogen from the entire global fertilizer industry
223 (Bodirsky et al. 2014). Hence, achieving the CO₂ mitigating challenge in which the soils play
224 an important role seems unlikely, with the availability of nitrogen being the limiting factor. It
225 can be suggested to focus on ‘over-exploited’ soils, and try to return them to agricultural
226 practices that assure that the soil organic carbon is not decreasing, and at least remains constant.

227 This will not only prevent increasing soil-related CO₂ emissions, it may also sustain overall
228 physico-chemical stability of the soil, with higher biomass yields.

229 The addition of organic materials, such as compost, peat, sewage sludge, and manure,
230 to increase soil organic carbon levels and enhance crop yield are well-established methods
231 (Diacono and Montemurro 2010). However, the use of compost and sewage sludge is often
232 impaired by the fact that these can contain heavy metals and organic pollutants arising from
233 pesticides, pharmaceuticals and personal care products (Andrade et al. 2010, Lozano et al. 2013,
234 Tou et al. 2017, Westerhoff et al. 2015). Animal manure is largely free from such pollutants,
235 but there is increasing concern that manure addition could result in agricultural soils that
236 accumulate antibiotic resistant bacteria (McGrath et al. 1995, Singer et al. 2016, Tou et al. 2017,
237 Udikovic-Kolic et al. 2014, Westerhoff et al. 2015, Zhu et al. 2013). Moreover, their overall
238 potential in terms of climate change mitigation is limited (Edenhofer 2014). Considering the above-
239 mentioned stoichiometric constraints in terms of nutrient, especially nitrogen, availability, and
240 limitations of conventional methods to increase carbon content of soils in the context of climate
241 mitigation, we suggest to use a novel approach in which MP is used as a slow-release organic
242 nitrogen fertilizer (see Figure 1). The production process is almost identical to the MP based food
243 and feed production processes described in the sections above, but with some key differences in
244 process requirements. The fermentation conditions are less strict in terms of hygiene, there is no
245 need for sterilization and consistent composition of the microbial biomass (*i.e.*, no need for
246 strict, pure culture conditions), and the final product does not require a 100% dry form, reducing
247 the drying requirements.

248 The production of this MP for slow-release nitrogen supply to the soil would still rely on
249 the use of Haber-Bosch process to produce the reactive nitrogen source (Figure 1). However, the
250 inorganic Haber-Bosch nitrogen fertilizer is transformed into an organic nitrogen form. Indeed, it
251 is integrated by the microbes into their cell biomass. The rationale behind this is that, worldwide,

252 inorganic nitrogen fertilizer has a very low use-efficiency of 40%, due to leaching, run-off,
253 denitrification and volatilization (Bodirsky et al. 2014). The concept is that upgrading this
254 mineral nitrogen to organic nitrogen in the form of MP increases the nitrogen use efficiency
255 with concomitant enrichment of the agricultural soil with organic matter. While many studies
256 highlight the positive impact of increasing the soil organic carbon on *e.g.*, agricultural yields,
257 carbon storage, nutrient and water retention as highlighted above, greenhouse gas fluxes from
258 agricultural soils are very large, complex and highly heterogeneous (Singh et al. 2010, Smith et
259 al. 2008, Xu et al. 2011). As such, under certain soil conditions, the increase in soil organic
260 carbon and organic nitrogen levels could even increase carbon dioxide, methane and nitrogen
261 emissions from the soil. Long-term trials would be essential to verify whether the addition of
262 MP results in increased storage of carbon in the soil organic matrix, coupled with low nitrogen
263 and highly potent greenhouse gas emissions.

264 A situation can be considered in which the total current global use of Haber-Bosch
265 fertilizer N of ~100 Mt/year (Zhang et al. 2015) would first be upgraded to MP. Considering a
266 typical C/N ratio for microbial biomass of 5 (Pikaar et al. 2017a), the theoretical potential of
267 MP to capture and temporarily store carbon in the soils reaches 0.5 Gt C/year (1.83 Gt
268 CO₂/year). This is substantially lower than the amount of carbon that has to be sequestered per
269 annum in soils according to the Paris mitigation challenges (*i.e.*, 1.2 Gt C) (Minasny et al. 2017).
270 Moreover, part of this MP carbon will be released from the soils over time, as it is biodegraded
271 to release nitrogen to the plants, thus decreasing the net carbon captured.

272 In addition to the limitations in carbon capture potential, this approach also comes with
273 considerable economic constraints. Considering the production cost of about 2800 US\$/tonne
274 HOB-based MP, which is equivalent to a cost of ~US\$1500/tCO₂ incorporated, it is clear that
275 these values are much higher than the economic costs for underground carbon storage of CO₂
276 or other available CCU routes (Service 2016). In contrast to the production of MP as human

277 food or animal feed, where the microbial biomass product has a high market value, MP for soil
278 application has to compete with alternative organic nitrogen fertilizers, such as (digested)
279 manure, sludge, kelp, feathers, and horn meal, as well as with inorganic fertilizer. These have
280 a relatively low market value, especially inorganic fertilizers, with prices for urea below
281 US\$500/t N (<http://www.indexmundi.com/commodities/?commodity=urea&months=60>). The
282 use of inorganic nitrogen is integrated in the MP production cost at a value of US\$112/tonne
283 MP, which is only a fraction of the overall production cost (4%). Even when considering high
284 carbon pricing schemes of US\$150–220/t CO₂ when implementing low stabilisation climate
285 targets such as the Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011), at
286 best, a carbon capture benefit of about US\$ 400/tonne MP can be achieved. Even under these
287 low stabilization climate targets, the organic nitrogen has a cost of about US\$2280 per 160 kg
288 N present in the MP, which is equivalent to 14000 US\$/tonne organic N. This is a factor 10 -
289 20 higher than the current commodity prices for inorganic and organic nitrogen.

290 In addition to the economic limitations describe above, there are also substantial energy-
291 related constraints. The production of MP for soil application requires substantial amounts of
292 renewable energy to produce hydrogen *via* water electrolysis. It would require about 3000
293 Gigawatt of renewable energy per Gt of MP produced (Pikaar et al. 2018). To put this amount
294 into a global context; the current installed capacity of renewables worldwide is only 912
295 Gigawatt (REN21 2017).

296

297 **Concluding remarks**

298 To deal with the climate change challenge, there is an urgent need to develop alternative routes
299 that can be implemented in the near future, capable of effectively avoiding carbon emissions
300 and/or capturing and utilizing carbon, that also have a positive impact on the environment and
301 the global economy. In this short paper, we examined the potential of autotrophic hydrogen-

302 oxidizing bacteria to capture and utilize carbon in the form of human food, protein rich animal
303 feed and slow-release nitrogen fertilizer. The production of food *via* the route of microbial
304 protein has the current potential to decrease the use of fossil fuel, water, pesticides, and land
305 use, to provide the global population with nutritious protein, but there may be issues with public
306 acceptability/demand and would require further research concerning its composition and
307 potential side effects. The production of microbial protein as animal feed *via* autotrophic
308 microbial biomass is not yet economically competitive. At current hydrogen production costs
309 through water electrolysis, the overall production price of microbial protein exceeds the costs
310 of conventional soybean and fishmeal. Yet, if in the future or in specific geographic regions the
311 cost can be decreased substantially or the as costs of conventional soybean and fishmeal
312 increase, this line of production of protein could become cost competitive.

313 The production of microbial protein for slow-release organic nitrogen fertilizer applications
314 is clearly of interest as a means to considerably increase the carbon content in agricultural soils,
315 and in light of its potential to reduce global nitrogen pollution. For many reasons, the dynamics
316 of such an increase in soil organic carbon storage through this route are hard to predict and
317 would — simply because MP is fully biodegradable — be reversible. Despite its theoretical
318 potential as a clean-tech solution to capture carbon and increase soil organic carbon content,
319 the current low market value of organic nitrogen fertilizer, the high-energy demands and current
320 production costs, severely limit the practical feasibility and potential as a climate change
321 mitigation tool. Although MP does not seem immediately ready for practice, this concept opens
322 new long-term perspectives to serve as a food and feed source, combined with its potential to
323 contribute to carbon capture and climate change abatement.

324

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