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A life cycle environmental sustainability analysis of microbial protein production via power-to-food approaches

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Abstract

Purpose Renewable energy produced from wind turbines and solar photovoltaics (PV) has rapidly increased its share in global energy markets. At the same time, interest in producing hydrocarbons via power-to-X (PtX) approaches using renewables has grown as the technology has matured. However, there exist knowledge gaps related to environmental impacts of some PtX approaches. Power-to-food (PtF) application is one of those approaches. To evaluate the environmental impacts of different PtF approaches, life cycle assessment was performed.

Methods The theoretical environmental potential of a novel concept of PtX technologies was investigated. Because PtX approaches have usually multiple technological solutions, such as the studied PtF application can have, several technological setups were chosen for the study. PtF application is seen as potentially being able to alleviate concerns about the sustainability of the global food sector, for example, as regards the land and water use impacts of food production. This study investigated four different environmental impact categories for microbial protein (MP) production via different technological setups of PtF from a cradle-to-gate perspective. The investigated impact categories include global warming potential, blue-water use, land use, and eutrophication. The research was carried out using a life cycle impact assessment method.

Results and discussion The results for PtF processes were compared with the impacts of other MP production technologies and soybean production. The results indicate that significantly lower environmental impact can be achieved with PtF compared with the other protein production processes studied. The best-case PtF technology setups cause considerably lower land occupation, eutrophication, and blue-water consumption impacts compared with soybean production. However, the energy source used and the electricity-to-biomass efficiency of the bioreactor greatly affect the sustainability of the PtF approach. Some energy sources and technological choices result in higher environmental impacts than other MP and soybean production. When designing PtF production facilities, special attention should thus be given to the technology used.

Conclusions With some qualifications, PtF can be considered an option for improving global food security at minimal environmental impact. If the MP via the introduced application substitutes the most harmful practices of production other protein sources, the saved resources could be used to, for example, mitigation purposes or to improve food security elsewhere. However, there still exist challenges, such as food safety-related issues, to be solved before PtF application can be used for commercial use.

Keywords Renewable electricity · Life cycle assessment · GHG emissions · Microbial protein · Sustainability · Power-to-food

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1 Introduction

Natural biogeochemical cycles of the Earth such as the carbon, nitrogen, and phosphorus cycles, as well as the water cycle are disturbed by human activities. The resulting changes in the balance of natural cycles have led to sustainability challenges like global warming, eutrophication, soil salinization, and a decline in available freshwater resources (e.g., The Royal Geographical Society 1998; Vörösmarty et al. 2010). While providing humanity with food, agriculture is a major actor imposing strains on natural cycles and resources (Cambpell

et al. 2017). Limited arable land and freshwater resources, climate change, and a growing human population are endangering global food security. On current trends, maintaining food security will become increasingly difficult, if present agricultural practices are not adapted to mitigate their effects on natural cycles (Calicioglu et al. 2019; Pretty et al. 2010; Vermeulen et al. 2012). The questions of food security and the environmental impacts of agriculture are well recognized and studied, and there is a need for a shift to a more action-oriented research agenda (Campbell et al. 2016).

Recently, a lot of research has focused on utilization of CO₂ into added-value products such as hydrocarbons (Godoy et al. 2017; Khunjar et al. 2012). Hydrocarbons can be produced using bacteria employing the Calvin cycle, in which carbon atoms from CO₂ are used to build three-carbon sugars, such as most species of H₂-oxidizing bacteria (Kuenen 1999). One focus of previous research has been power-to-X (PtX) technologies to produce hydrocarbons from renewable electricity via water electrolysis and CO₂ from different sources (Koj et al. 2019; Chehade et al. 2019). There is no formal definition for PtX applications, but commonly, they refer to technologies producing something from renewable electricity through water electrolysis and additional processes (e.g., Koj et al. 2019; Uusitalo et al. 2017; Zhang et al. 2017). This definition of PtX is used in this paper. The research interest towards PtX is partly due to the forecast rapid growth of renewable energy capacity using energy generation resources such as solar and wind power, and due to environmental challenges, such as anthropogenic climate change and eutrophication, humanity has to solve to move towards sustainable development. The increasing share of renewables does not happen without problems as they cause fluctuation in energy generation resulting in occasional oversupply. To overcome this problem, different demand response solutions are proposed (e.g., Aghaei and Alizadeh 2013; Zehir et al. 2016). Fortunately, PtX applications can be designed to utilize electricity as a demand response, when electricity prices are low, and to balance the grid (Uusitalo et al. 2017; Zhang et al. 2017). Several life cycle assessment studies have shown that PtX processes in most cases lead to reductions in climate change impacts compared to fossil hydrocarbons (e.g., Uusitalo et al. 2017; Zhang et al. 2017; Sternberg and Bardow 2015). Power-to-gas is one example of a PtX application and it is seen as a promising technology for large-scale and long-term energy storage (Zhang et al. 2017).

When considering agricultural products, it is possible to produce bacterial-based protein-rich biomass, also called microbial proteins (MP), for feed and food purposes using a PtX approach. H₂-oxidizing bacterium can produce protein-rich biomass suitable for feed or food purposes by utilizing H₂, O₂, and CO₂ with additional substances. H₂ and O₂ can be produced via water electrolysis and CO₂ can be provided from sources such as air. (Sillman et al. 2019) Here, the approach is

called a power-to-food (PtF) application. The main components of the PtF approach consist of a CO₂ source, bioreactor, water electrolysis, and post-processes for separating biomass from the cultivation medium and for drying. The possibility to produce biomass using the H₂-oxidizing bacterium *Cupriavidus necator* has gained interest in previous studies due to high electricity-to-biomass efficiencies (e.g., Liu et al. 2016; Yu et al. 2013; Yu 2014). In addition, unlike traditional protein production, production of MP is seen as climate independent as the climatic conditions do not influence on the growing conditions of a closed production system and bacterium has a fast growth rate (Upadhaya et al. 2016; Srividya et al. 2014).

The nutritional value of some MP sources, such as MP from *C. necator*, is comparable to nutritional recommendations and to traditional protein sources such as fishmeal and soymeal based on essential amino acids that must be supplied in feed, as the animals themselves cannot synthesize them (Srividya et al. 2014; Volova and Barashkov 2010; WHO/FAO 1973.). MP from *C. necator* has been shown to be useful for 25–50% of the diet depending on the species and age of the animals (Volova and Barashkov 2010). Protein content of bacterial MPs from 50 to 83% is found in literature. However, the usable protein content is usually lower than the absolute raw protein content of the bacterial biomass. (Anupama and Ravindra 2000; Kunasundari et al. 2013) There are three main types of MP sources, which are fungus, yeast, and bacterial protein. The doubling time of bacterial protein is the fastest among the types of MP sources. (Srividya et al. 2014.) Quorn, spirulina, UniProtein®, and FeedKind® are examples of MP-based products available in the market.

Although bacterial MP is seen as an environmentally sustainable alternative to conventional protein sources, there exist only few MP-related LCA studies focusing on food or feed production. (e.g., Cumberlege et al. 2016; Knudsen et al. 2016). LCA study has been conducted for a bacterial MP known as FeedKind®, which is produced by the biotechnology company Calysta. FeedKind® is a bacterial protein source produced for feed purposes. The bacterium uses methane to build up its biomass, thus it is called MP via methane in this study (Cumberlege et al. 2016). Another example of a MP source that has undergone LCA is microalgae. Their use as food or feed has gained interest in recent years, but the research has mainly focused on their utilization as a raw material for biofuel production (Aresta et al. 2005; Mata et al. 2010; Sander and Murthy 2010; Quin and Davis 2015). Pikaar et al. (2018) used the MagPie model (Pop et al. 2010) to simulate avoided cropland expansion areas, greenhouse gas emissions, and nitrogen pollution impacts of several bacterial MP production pathways. The biggest avoided impacts were gained by using MP via water electrolysis, which is a similar kind of pathway to produce MP than the studied PtF application has. In addition, it has been shown based on quantitative literature review that it is possible to produce MPs with less direct land

occupation area and freshwater use than conventional protein production by using renewable energy, in situ water electrolysis, direct air capture technology, and post-processes to separate microbial biomass from cultivation medium (Sillman et al. 2019). However, to the extent of our knowledge, there are no LCA studies comparatively evaluating MP production via different PtF approaches, even though there are several LCA studies focusing on different PtX technologies (Koj et al. 2019). Different PtF approaches have many technological system modifications, of which the energy sources used, origin of substances needed in the production processes, the bacterium species used, and the selected process optimization are a few examples. These technological system differences influence different categories of the environmental life cycle impacts of the production processes; thus, it is essential to know which kind of technological choices should be preferred in terms of environmental sustainability.

As the overall environmental impact of various system modifications of PtF applications is not known, it is necessary to compare how different system modifications impact LCA categories and which approaches have the least environmental impacts. The sustainability can be evaluated by investigating categories related to the planetary boundaries presented in Steffen et al. (2015). The concept of planetary boundaries defines a safe operational zone for humanity for nine environmental activity categories. Water use, land use, biodiversity loss, climate change, and nutrient flows are examples of activities in which agriculture has a major role and which have either exceeded or are close to exceeding safe operation spaces (Cambpell et al. 2017; Steffen et al. 2015). The selected categories for evaluating the sustainability of different modifications of the PtF process are related to climate change, land use, freshwater use, and eutrophication. As regards impacts related to biodiversity loss, there are severe limitations to including biodiversity impacts in LCA methodology (Notamicola et al. 2017). Therefore, biodiversity impacts are not assessed in this study.

The aim of this study is to investigate whether a climate-independent PtF technology can be designed to produce protein-rich biomass that has minimal sustainability impacts compared to other protein-rich sources and, furthermore, to establish which PtF system modifications are the most environmentally sustainable. The hypothesis is that protein via PtF application can be designed to cause less environmental impacts than comparable protein sources. The comparable protein sources are soybean and a few other MPs. Soybean is chosen as it is a widely used plant-based protein source and the nutritional value is comparable with protein via PtF application. Other protein sources are selected to compare the sustainability of PtF to other MPs. If the hypothesis is true, the knowledge can be used for mitigation of the impact of food systems on the natural environment. For instance, by substituting protein sources with higher land use impact with

ones having lower land use impact, the saved land could be used, e.g., as sinks for atmospheric CO₂. This study provides novel information about how food production can be integrated with electrical power production via PtF applications and information about the environmental impacts of PtF applications.

2 Materials and methods

The study was carried out using a life cycle assessment (LCA) methodology based on the ISO 14040 (2006) standard, and GaBi 6.0 life cycle assessment software was used in the life cycle modeling and impact assessment. A professional database of GaBi software was used to provide initial data for the model, particularly information related to inputs such as the impact of nutrient and energy production. Additional initial data, for example, the amount of inputs, were gathered from literature.

2.1 Goal and scope definition

The aim is to assess four different impact categories related to planetary boundaries. GWP can be used to measure impacts related to climate change. The land occupation indicator is describing land use. Eutrophication potential is describing nutrient flows and blue-water consumption describes freshwater use. Blue-water consumption does not include water scarcity issues. These impacts can be compared with impacts of alternative protein sources.

A base setup was used as a reference for evaluation of the environmental impacts of different modifications of PtF. The base setup is described in Section 2.2.6, and the selected PtF technologies are described in Sections 2.2.1, 2.2.2, 2.2.3, 2.2.4, and 2.2.5. To evaluate the sustainability of the PtF approaches, the environmental impacts of MP production via PtF are compared with other MP products and with conventional plant-based protein sources. In this study, the production of MP via PtF is assumed to be in Europe. Soybeans are a widely used and efficient plant-based protein source with high protein content and high yields and have similar protein quality than the studied MP, and Europe imports large quantities of soybeans (FAOSTAT 2019; Volova and Barashkov 2010; WHO/FAO 1973). These characteristics make soybean protein a well-suited protein for comparison. The environmental sustainability comparison between the modeled MP production, other MPs, and soybean protein, based on literature, was performed using an attributional approach. Sensitivity analysis was performed using a one-at-a-time method for base setup.

Different food products are not equal as their nutritional values per kilogram of product vary. Consequently, a direct comparison based only on the weight of the product is unreasonable. Proteins have previously been used to evaluate food security (Diaz-Bonilla et al. 2000) and the idea of MP

products is to act as substitute proteins for conventional protein sources; thus, 1 kg of protein is used as a functional unit.

2.2 Life cycle inventory analysis

The cultivated bacterium species is *C. necator* (also called *Ralstonia eutropha* and *Alcaligenes eutrophus*) (Aragno 1998), which can produce microbial biomass with a usable protein content of 50 to 65% of dry biomass. (Anupama and Ravindra 2000; Kunasundari et al. 2013; Yu 2014; Volova and Barashkov 2010). In this study, a protein content of 60% is used when environmental impacts are modeled as the production process is assumed to be designed as close to optimal.

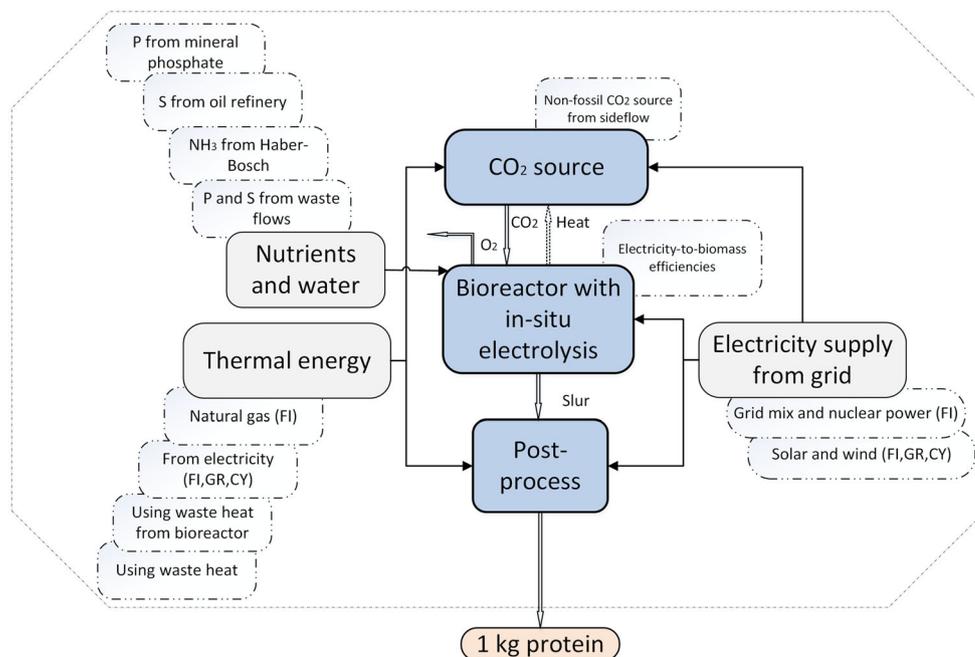
The studied processes for H₂-oxidizing-based MP production are amine production, CO₂ sources, electricity generation, bioreactors with in situ and external electrolysis, and post-processes for biomass cultivation and water removal. The production processes are considered closed systems with no run-offs. The closed system refers to a process in which the material and energy flows can be controlled. The controllable processes make it possible to efficiently utilize nutrients with no nutrient run-offs to the surrounding environment. Major material and energy flows are included in the cradle-to-gate assessment. The construction phase of production facilities, minor nutrients in the cultivation medium, and minor unit processes, e.g., cultivation medium pumping into the bioreactor are neglected based on cutoff criteria. As the production facilities can be located nearly everywhere, the logistics impacts are neglected. The system boundary with the different process modifications of the cradle-to-gate assessment is presented in Fig. 1.

2.2.1 Nutrient and CO₂ consumption

Nutrients included in the LCA models are ammonia, phosphates, and sulfur. Other substances are neglected due to their low concentration in the solution medium and due to data availability issues. The cultivation medium contains several minerals, e.g., KH₂PO₄ and MgSO₄, with concentrations of a few grams per liter (e.g., Akiyama et al. 2003; Liu et al. 2016; Volova and Barashkov 2010). Based on stoichiometry of production of 1 kg biomass of *C. necator*, approximately 1.76 kg of CO₂ and 0.16 of NH₃ are needed (Liu et al. 2016). The amount of carbon is used to estimate the required amounts of phosphates (P) and sulfur (S). Molar ratios of 1:50 P:C and 0.03:1 S:C are typical for aquatic bacterium (Faberbakke et al. 1996), which accounts for approximately 0.141 kg of S and 0.140 kg of P per 1 kg of biomass. Nutrient use and CO₂ utilization efficiencies are assumed to be 100% as the production process can be designed to be a closed system making it possible to utilize nutrients until they are completely depleted (Lee 2015).

NH₃ is assumed to be produced by the Haber-Bosch process and the H₂ needed is produced from natural gas, which is the most commonly used route to produce NH₃. S is assumed to be derived as a side product from an oil refinery and P from mineral phosphate containing 32% of P₂O₅. The environmental impacts of S, NH₃, and P are modeled using average impacts found in the GaBi database for the EU region. A few studies have proposed taking S and P from wastewaters (e.g., Matassa et al. 2015). Impacts, if S and P are taken from wastewaters, are studied via one of the system modifications.

Fig. 1 System boundaries of the studied PtF approaches. Boxes with dashed lines represent modifications of PtF technologies



2.2.2 Electricity and thermal energy generation

In this study, renewable wind and solar energy are considered as the main electrical energy sources for the PtF applications. However, climatic conditions affect the environmental impacts of renewables, thus the location of electricity generation can have a major role, when thinking overall impacts of PtF applications. To study how latitude affects the overall environmental impacts of PtF systems, the production locations selected for study are in different latitudes in Europe. The used production values are average values of the selected locations, which are Finland, Germany, and Cyprus. Finland represents conditions in Northern Europe, Germany conditions in Central Europe, and Cyprus conditions in Southern Europe. The effect of latitude is studied for renewable energies only. Of course, it is possible to use sources other than wind or solar power for electricity generation, and thus the impacts of non-renewable electrical energy sources are also studied. Electricity sources compared are solar energy from photovoltaics, wind energy, nuclear energy, and the average electricity mix in Finland. GaBi databases are used to model impacts of electricity production.

Thermal energy is produced using either high-temperature heat pumps, combustion of natural gas, or energy taken from point sources producing waste heat. Natural gas is a widely used fossil fuel-based energy source with relatively low environmental impact; thus, its use is considered in this study. High-temperature heat pumps are preferred over basic heat pumps, because of the required temperature to regenerate amine-based sorbents in the direct air capture (DAC) process (Section 2.2.3). Liu et al. (2016) have estimated that up to 4.54 kWh thermal energy per kg biomass can be formed in a bioreactor, but H₂-oxidizing bacteria grow at relatively low temperatures (approximately 30 °C), which makes utilization of the excess heat difficult. Thermal energy created in the bioreactor is thus not considered to be used in this study.

The required electrical energy of heat pumps to produce thermal energy is dependent on the coefficient of performance (COP) value. COP refers to the ratio of useful heating or cooling provided to the work required. A heating COP value of 2.1 to 2.6 has been achieved with a temperature source of 30 to 120 °C using high-temperature heat pumps but even higher COP values are possible (Arpagaus et al. 2018). In this study, a COP value of 2.5 is used when producing thermal energy using electricity.

2.2.3 Source of CO₂

Two sources of CO₂ are studied in this LCA study. The base setup consists of direct air capture technology (DAC). DAC is seen as a plausible technology capable of reducing CO₂ from ambient air that can be used to mitigate climate change (Sanz-Perez et al. 2016). The second option uses a side flow of pure

CO₂ from non-fossil sources without additional material and energy requirements. For example, a fermentation process can supply CO₂ to the bioreactor.

DAC technology uses amine-based sorbents to separate CO₂ from air. CO₂ is absorbed into amines, which can be regenerated at a temperature of approximately 100 °C (Climeworks 2019). During the regeneration process, the bound CO₂ is released and fed to the bioreactor, where the bacterium uses it to build up its biomass. However, small amounts of amines are consumed during the process. The amine production needed has been modeled as described by Zhang et al. (2017). According to Zhang et al. (2017), no information is publicly available regarding the actual processes that are needed to produce the amines used in the Climeworks DAC device. Thus, general organic chemicals are used to estimate environmental impacts from amine production. The amount of consumed organic chemicals is 0.0036 kg per kilogram of produced biomass, which is calculated using the weight ratio of needed CO₂ and consumed organic chemicals. The impacts of amine consumption are estimated by using the GaBi database of generic organic chemicals including amine. The electricity and thermal energy requirement of the DAC device are 1.8–2.5 kWh/kg_{CO₂} and 0.35–0.45 kWh/kg_{CO₂}, respectively (Climeworks 2019).

CO₂ is not the only substance that can be provided by a DAC device. If there is moisture in the air and the air temperature is sufficient, liquid water is formed during the separation process. In humid conditions with a temperature of + 25 °C, the molar ratio of separated H₂O per CO₂ is 4.9 (Elfving et al. 2017). If the separated water does not hold any harmful impurities, it can be used to replace fresh water consumed in production processes. Based on stoichiometry, the amount of formed water is 3.53 kg per 1 kg of biomass. In the case of provided CO₂, the purity of the CO₂ can exceed the purity levels of 99.99% by volume (IPCC 2005).

2.2.4 Electricity-to-biomass efficiency of a bioreactor

Using in situ electrolysis in a bioreactor to grow H₂-oxidizing bacterium is an old innovation (Schlegel and Lafferty 1965). Since that time, the electricity-to-biomass efficiency has gradually improved (e.g., Liu et al. 2016; Schuster and Schlegel 1967; Torella et al. 2015). Liu et al. (2016) achieved an efficiency of 54% by using in situ water electrolysis, which corresponds to 9.86 kWh per produced biomass. In contrast, efficiencies of 4.8% and 13% were reported in the studies of Schuster and Schlegel (1967) and Torella et al. (2015), respectively. When studying the environmental impacts, a base situation uses state-of-the-art electricity-to-biomass efficiency with electrical consumption of 9.86 kWh. In one case, the electricity-to-biomass efficiency is assumed to be in the range of 13–54% to demonstrate the importance of the bioreactor

process on the overall impacts. In that case, the energy consumption is 25 kWh per kilogram of biomass.

The conventional approach for providing a bioreactor with H₂ and O₂ is to use external water electrolysis rather than in situ electrolysis. In such cases, water electrolysis can be considered as a separate unit process. The challenge of external electrolysis is the low mass transfer of H₂ and O₂ to aqueous solution, which inhibits the growth rate of bacterial biomass (Yu 2014). In addition to H₂ and O₂, also CO₂ has to be fed into the bioreactor. Typically, the used volumetric ratio of CO₂, O₂, and H₂ gases for growth of a hydrogen-oxidizing bacterium is 1:2:7 (e.g., Volova et al. 2013; Zhila et al. 2015) and, thus, the amount of H₂ and the H₂ conversion efficiency to biomass determine the energy requirement of a water electrolysis process. Based on stoichiometry of *C. necator*, the amount of required H₂ is 71.4 g per kg_{biomass} (Liu et al. 2016). Matassa et al. (2016) have achieved H₂ conversion efficiency of 81% on average using a continuous reactor type, and thus, the required amount of H₂ is 88.1 g per kg_{biomass}. In this study, proton exchange membrane (PEM) water electrolysis is used to produce H₂ because of its compact structure, wide partial load range, and high energy efficiency (Chi and Yu 2018). The system efficiency of PEM water electrolysis has been reported to vary in a range of 62–77% defined by the higher heating value (HHV) of hydrogen of 39.41 kWh per kg_{H₂} (Decourt et al. 2014). A stack efficiency of 80% (HHV) has been measured for a commercial 5 kW PEM stack under differential pressure (Koponen et al. 2017). The Balance of Plant (BOP) energy consumption of the hydrogen production unit has been estimated to be 8% of the PEM stack energy consumption including the stack power supply losses (Colella et al. 2014). Therefore, the overall energy consumption of the PEM electrolysis based H₂ production unit is estimated to be 53 kWh per kg_{H₂} and 4.7 kWh per kg_{biomass}.

2.2.5 Post-processes

The post-processes are designed similarly than described in study Sillman et al. (2019). It can be assumed that the cultivation medium has a biomass concentration of 2.5% (Lee 2015). First, the concentration of bacterial biomass is increased to 20% from 2.5% by the help of centrifugation, thus 40 l of cultivation medium needs to be processed. This process requires 0.05 kWh electrical energy per kg bacterial biomass based on energy consumption of 1.35 kWh per m³ (Davis et al. 2016). Then, the remaining water is evaporated until the biomass concentration is 90%. The evaporation requires approximately 2.91 kWh thermal energy with the efficiency of 84%. After the post-processes the bacterial biomass contains residue water, thus, 0.11 kg of water is consumed per kg bacterial biomass. There exist other technical solutions for water removal than evaporation and centrifugation, such as

filtration, flash drying, or grinding. In this study, these other technical alternatives are not modeled.

2.2.6 Studied system modifications

The base setup acts as a comparative for different system modifications when the environmental impacts are analyzed. The base setup consists of the DAC process, the in situ electrolysis with electricity-to-biomass efficiency of 54%, the post-processes described in Section 2.2.5 Ammonia is produced via the Haber-Bosch process, sulfur is taken from side flow of an oil refinery, phosphor is taken from mineral phosphate, and the required thermal energy is produced with electricity. The electricity is generated with PV solar power in Finland. The material and energy flows of the base setup of the PtF processes are presented in Table 1.

The study models the base situation and 13 modified technological setups for MP production using the bacterium *C. necator*. Country-specific and process-specific data for the modeling are taken from GaBi databases. Grid mix, plant production, raw material for energy production, and electricity distribution are included in environmental impacts of electricity. When studying the impacts of different electricity sources and locations, the modifications are named according to location and energy source. The system modifications of the PtF processes are presented below:

- Base setup: Material and energy flows are given in Table 1. The selected technologies and energy sources are a bioreactor with in situ electrolysis; solar energy produced in Finland; thermal energy produced using a high-temperature heat pump; DAC is used to provide CO₂; and post-processes are designed according to Section 2.2.5.
- Mod1: The electricity-to-biomass efficiency of the bioreactor is changed from 9.86 to 25 kWh.
- Mod2: External electrolysis is used instead of in situ electrolysis. Energy flows are modeled according to Section 2.2.4.
- Mod3: The thermal energy for DAC and the post-processes is produced using natural gas.
- Mod4: The thermal energy is taken from waste heat sources, which are considered emission free.
- Mod5: S and P are taken from wastewater flows, which are counted as emission-free sources.
- Mod6: CO₂ is taken from waste flows of organic sources (e.g., fermentation). The CO₂ is counted as a neutral emission source resulting in zero GHG emissions.
- FI_{nuc}: The electricity used is nuclear energy in Finland.
- FI_{win}: The electricity used is wind power in Finland.
- FI_{mix}: The electricity used is the grid mix in Finland.
- CY_{sol}: The electricity used is photovoltaic solar power in Cyprus.
- CY_{win}: The electricity used is wind power in Cyprus.

Table 1 Energy and material flows of processes of the base situation per 1 kg of produced biomass

| Direct air capture | | | | | | |
|--------------------|--------------------------------|-----------------------------------|-------------------------------------|-------------------|----------------------|-------------------|
| Inputs | Electricity [kWh] ^a | Thermal energy [kWh] ^a | Organic chemicals [kg] ^b | Air* | | |
| | 0.71 | 3.78 | 0.0036SSSS | | | |
| Outputs | CO ₂ [kg] | water_cond [kg] | | | | |
| | 1.76 | 3.53 | | | | |
| Bioreactor | | | | | | |
| Inputs | Electricity [kWh] | Mineral phosphate [kg] | Sulfur [kg] | Ammonia [kg] | CO ₂ [kg] | Water [kg] |
| | 9.86 ^c | 0.140 ^d | 0.14 ^d | 0.16 ^c | 1.76 ^c | 0.11 ^c |
| Outputs | Biomass [kg] | O ₂ [kg] | | | | |
| | 1 | 1.31 ^c | | | | |
| Post-process | | | | | | |
| Inputs | Electricity [kWh] | Thermal energy [kWh] | | | | |
| | 0.39 ^e | 2.91 ^e | | | | |
| Outputs | Biomass [kg] | Water [kg] | | | | |
| | 1 | 0.11 ^c | | | | |

^a Climeworks (2019), ^b Zhang et al. (2017), ^c (Liu et al. 2016), ^d Section 2.2.1, ^e Section 2.2.5, *amount of air is not measured, but the amount of separated water and CO₂ are known

- GEsol: The electricity used is photovoltaic solar power in Germany.
- GEwin: The electricity used is wind power in Germany.

2.2.7 Other reference systems: soybean and selected MP productions

FeedKind® is a bacterial MP using methanogenesis to build up its biomass. The powder form of FeedKind®, which does not hold any substances other than bacterial biomass has a carbon footprint of 2.229 kg_{CO2} per kg_{protein} but can achieve a lower carbon footprint value if the natural gas used in the process is replaced with biogas. Water consumption for the powder form of FeedKind® is approximately 10 kg water per kg protein, and land occupation is 0 m² per kg protein. (Cumberlege et al. 2016). The average value of protein content of Quorn, mycoprotein, is 0.16 kg per kg product, which is used to evaluate environmental impacts of mycoprotein production. Mycoprotein has global warming potential (GWP) and land use values of 38.4–15 kg_{CO2-eq} and 2.6–7.5 m² per kg protein, respectively (Head et al. 2011; Smetana et al. 2015). Water requirement for mycoprotein production and eutrophication values for MP via methane and mycoprotein production were not found in literature.

Soybean is one of the most important plant-based protein source for feed and human food (FAOSTAT 2019). However, it has been reported to have various negative environmental impacts, for example, from land use in tropical regions (e.g. Barona et al. 2010; Feamside 2001). Eutrophication, land use,

water use, and GWP impacts of soybean production are highly dependent on the production practices used and the growing location, and thus the values used for comparison does not cover all the production practices there are. However, they provide directional estimate for impacts of soybean production. Protein content of soybean from varies 32 to 43% per kg product. Average protein content of 35% per kilogram of soybeans (Damian et al. 1999; Dornbos and Mullen 1992) is used for impact estimations on soybean production. Comparable eutrophication value of soybean protein production for P-equivalent is 0.019 kg per kg protein (Jekeyinfa et al. 2013). Climate change impact varies from 0.89 to 3.74 kg_{CO2-eq} per kg protein, and land use varies from 5.24 to 6.04 m² per kilogram of annual protein production. Water consumption of soybean production is approximately 6.3 kg of water per kg protein (Adom et al. 2012; da Silva et al. 2010; Mekonnen and Hoekstra 2012).

2.3 Life cycle impact analysis

The GaBi software is designed to measure different impacts on the environment rather than the impact allowed within planetary boundaries. However, knowledge gained from LCA studies can be used to design systems that cause the least impact on the environment. By substituting systems with high environmental impacts with those having less impact, the overall burden on the environment decreases and the system moves towards the safe operation space. In this paper, the environmental impacts of protein production is the system studied.

Global warming potential, land occupation indicator, eutrophication potential, and blue-water consumption are modeled for every system modification. GWP and eutrophication potential are modeled using CML 2001–2015 GWP 100 weighting and the land occupation indicator is used to model land use. Blue-water consumption includes freshwater consumption and excludes rainwater. The water use has been calculated using weight as a measure and it does not account for regionalized impact in terms of water scarcity.

3 Results

Global warming potential, land occupation indicator, eutrophication potential, and blue-water consumption of PtF system modifications are investigated in Section 3.1. The results are discussed in Section 3.1.5.

3.1 GWP, land occupation, eutrophication, and blue-water consumption of system modifications

Life cycle GWP, land occupation, eutrophication, and blue-water consumption of different system modifications are presented in Sections 3.1.1, 3.1.2, 3.1.3, and 3.1.4. The different system modifications are compared to the base situation to ascertain critical processes as regards the studied impacts. The impacts of different system modifications are modeled from Mod 1 to Mod 6. For modifications named FI, CY, or GE, only electricity sources and the location of energy production have been changed. For each system variation, a best-case technological setup is formed based on the best-case scenario in the impact category of GWP.

3.1.1 Global warming potential

For the different technological setups of PtF, the electricity-to-biomass efficiency of the bioreactor and the method used to provide the process with thermal energy and CO₂ have the greatest influence on GWP. Of the studied systems, the best-case scenario is to use point sources of waste heat and external water electrolysis and to take the required CO₂ and nutrients S and P from side flows. The least favorable solutions are to use low electricity-to-biomass efficiency bioreactors and a DAC process using natural gas as a thermal energy provider (Fig. 2).

The electricity source has the biggest impact on the GWP, as seen in Fig. 2. FI_{nuc} has the lowest impact and the highest impact is found with FI_{mix}. FI_{nuc} uses nuclear power and FI_{mix} uses the current grid mix in Finland as the energy source. However, because of the increasing interest of PtX processes using renewables are increasing, this study focus on impacts of renewables. The availability of solar and wind energy is dependent on climate conditions, and the location of the production facilities thus has an impact on GWP when

wind or solar energy sources are relied on. Only FI_{mix} using the Finnish grid mix as the energy source causes higher GWP impact than the base situation. Wind energy and solar energy in southern latitudes cause the lowest GWP impact values of the studied renewable energy sources.

When combining the best-case system modifications of the studied systems using solar and wind energy in different locations, the MP production causes approximately 1.00 kg_{CO₂-eq} kg_{protein}⁻¹ and 0.81 kg kg_{CO₂-eq} kg_{protein}⁻¹ in Cyprus, 1.11 kg_{CO₂-eq} kg_{protein}⁻¹ and 0.83 kg_{CO₂-eq} kg_{protein}⁻¹ in Germany, and 1.15 kg_{CO₂-eq} kg_{protein}⁻¹ and 0.82 kg_{CO₂-eq} kg_{protein}⁻¹ in Finland, respectively. The best-case system modifications consist of external water electrolysis and waste or side flow sources of CO₂, thermal energy, and nutrients. Ammonia production has a high impact value in the best-case system modifications, accounting for 64–90% of total GWP impacts.

3.1.2 Land occupation indicator

The studied system modifications in Fig. 3 show that the electricity used and the thermal energy source have the greatest influence on the land occupation indicator. The impacts caused by production facilities are neglected. The nutrients S, P, and NH₃ have low impact on the land occupation indicator. In best-case system modifications, described in Section 3.1.1, the impacts of PtF using solar energy and wind energy are 0.060 m² kg_{protein}⁻¹ year⁻¹ and 0.029 m² kg_{protein}⁻¹ year⁻¹ in Cyprus, 0.084 m² kg_{protein}⁻¹ year⁻¹ and 0.036 m² kg_{protein}⁻¹ year⁻¹ in Germany, and 0.085 m² kg_{protein}⁻¹ year⁻¹ and 0.031 m² kg_{protein}⁻¹ year⁻¹ in Finland, respectively.

3.1.3 Eutrophication potential

The impact of the eutrophication potential of the different system modifications was modeled for P equivalent. Ammonia production and the used electricity source have the greatest impact on eutrophication (Fig. 4). The best-case setup resulted in 0.000333 kg_{P-eq} kg_{protein}⁻¹ and was found for wind energy in Cyprus.

3.1.4 Blue-water consumption

Of the studied impact categories, the blue-water consumption shows the biggest difference for the studied system modifications (Figs. 3, 4, and 5). Although direct water consumption is highest in the bioreactor process, in most of the cases the biggest life cycle water consumption is caused by electricity generation and DAC processes. The water consumption in the process is around 0.8 l per produced kg_{protein} (Table 1). Using solar energy as an energy source consumes significantly more water compared to the solution using wind energy. The best-case setup using wind or solar energy resulted in 1 kg_{water} kg_{protein}⁻¹ and 3.8 kg_{water} kg_{protein}⁻¹ in Cyprus, respectively.

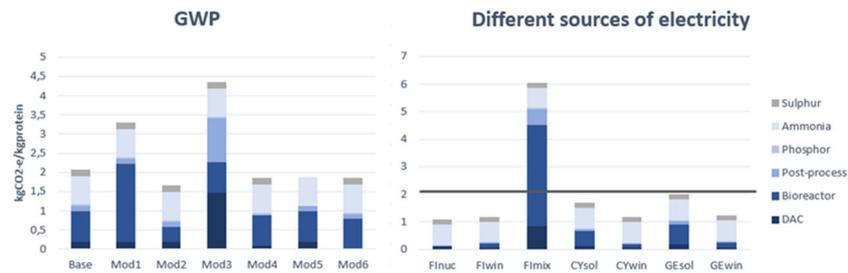


Fig. 2 Global warming potential of different system modifications of PtF application. PtF application with different material sources and technologies (left). The sensitivity of electricity source and location to overall impacts (right). Highlighted horizontal bar shows GWP value of the reference base setup

3.1.5 Environmental impacts of PtF setups compared to other protein sources

When comparing impacts of best-case system modifications for bacterial MP produced via PtF in Cyprus to the impacts of other protein sources taken from literature (Section 2.2.7; Table 2), it can be seen that PtF-based MP production causes minimal environmental impacts with only the life cycle blue-water consumption being higher than that of soybean protein production. GWP of PtF protein is lower than MP via methane, Quorn, and the average GWP value of soybean production. The best-case systems can cause between two to two and a half times lower GWP impacts compared to the average impact of soybean production. In the case of land use, the PtF process has significant advantages compared to mycoprotein and soybean production and has the same kind of land requirements as MP via methane. Life cycle water consumption can be designed to be lower than MP via methane and soybean production but using PV as an energy source consumes significantly more blue water than using wind as the energy source. Considering only the process stoichiometry, the process can produce more water than it consumes, if DAC is implemented in humid conditions. The production of MP consumes approximately 0.18 kg of water per kg protein and produces approximately 5.89 kg of water per kg protein. The capacity to produce water can be beneficial in areas having a high demand for water but limited water resources. In the case of the eutrophication, PtF causes tenfold less eutrophication impact than soybean production.

4 Discussion

The LCA in this study shows that compared to soybean production, bacterial biomass can produce protein many times faster with less water use, lower land area requirements, less eutrophication, and lower GWP impacts. Especially the best-case setups of the studied technologies can produce high-quality bacterial-based protein with significantly reduced environmental impacts. Even when best-case setups of PtF applications are not used, the environmental impacts in the studied categories are in many cases smaller than the other protein sources studied (Table 2; Figs. 2, 3, 4, and 5). The exception is blue-water consumption, especially when solar energy and DAC is used, but then again, the direct water consumption is not so great. Therefore, the PtF technology has many design options causing relatively small environmental impacts. The flexible design can be beneficial from the perspective of optimal design for local resources and local climate conditions. For instance, the production system can be designed as a closed system, and as such, it will not cause nutrient runoff to the environment. In addition, the production is location and climate independent (Srividya et al. 2014).

The life cycle assessment consists of the major material and energy flows of the PtF applications based on secondary data found in literature and by manufacturers. The impacts of amine consumption of the DAC process are based on estimates of generic organic chemicals; thus, the impacts of precise amine-based chemicals should be investigated. The facilities for MP production, minor nutrients in the cultivation

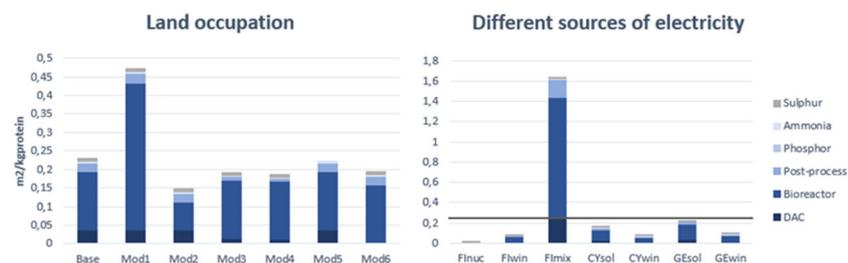


Fig. 3 Land occupation of different system modifications of PtF application. The land occupation indicator estimates the annual area required for protein production. PtF application with different material

sources and technologies (left). The sensitivity of electricity source and location to overall impacts (right). Highlighted horizontal bar shows Land occupation indicator value of the reference base setup

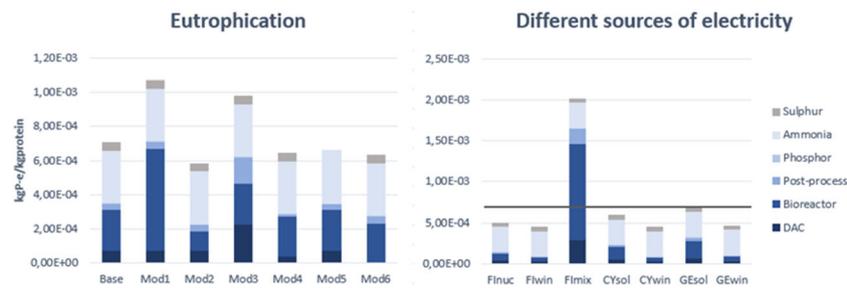


Fig. 4 Eutrophication values based on phosphorus equivalent of PtF systems. Material and energy inputs and outputs of energy production and substance needs are included in the life cycle analysis. PtF applications with different material sources and technologies (left). The

sensitivity of electricity source and location to overall impacts (right). Highlighted horizontal bar shows the eutrophication value of the reference base setup

medium and minor unit processes were omitted from the study. In addition, the safety-related aspects, such as contamination and pH control, might slightly cause impacts during the maintenance, which were also omitted. The cumulative impacts of these omitted materials, unit processes, and facilities should be investigated, to gain a better understanding of the lifetime impacts of the PtF applications. The energy and material requirement of the studied bioreactors were laboratory-scale reactors; thus, the material and energy requirement of bioreactors with larger capacity should be tested, although scaling up the capacity would appear to be unproblematic (Reed et al. 2015). Overall, this study gives valuable information when designing sustainable PtF systems.

The countries of the EU import millions of tons of soymeal and soybeans for food and feed purposes. Most of the imported soybeans and soymeal comes from the United States of America and South America. Imports from South America are problematic as there are many sustainability challenges related to soy crop production, for instance, challenges related to soybean farming in former rainforest areas (Barona et al. 2010; Fearnside 2001). By substituting imported soymeal and soybeans produced in South America with protein produced via a PtF system, many environmental impacts can be alleviated, and the food production system can move towards remaining within planetary boundaries as regards climate change, nutrient flows, water use, and land use. It should be noted that the results of this study give an overview of the impacts but do not account for all indirect

impacts in transition from one protein source to another. In addition, the amount of substitutable protein is limited and protein from soybean is not the only source the MP via PtF can substitute. For example, Pikaar et al. (2018) estimate that approximately 10–19% of the protein content in feed is substitutable. However, the MP via PtF is not yet commercialized; thus, the production process must undergo several safety-related tests before it can be used either for food or feed purposes (Dominique et al. 2016).

Although biodiversity is a major category in environmental impact analysis, it is not quantitatively researched in this study. Biodiversity is not commonly studied in life cycle impact assessments due to difficulties measuring biodiversity impact reliably without knowledge of local conditions (Notamicola et al. 2017). However, as pesticides and herbicides are not used in the PtF production processes (Srividya et al. 2014) and there is a possibility to use non-arable land for production facilities, there is a strong indication that the biodiversity impact of MP production is minimal compared to traditional protein production in agriculture. For instance, the worldwide reduction in insects is one alarming indicator of the collapse of our surrounding biodiversity. The main drivers of insect reduction are intensive agriculture and widespread use of pesticides (Sánchez-Bayo and Wyckhuys 2019; Geiger et al. 2010). Furthermore, the majority of soybeans and soymeal imported to the EU originates from South America, mainly Brazil and Argentina. These areas have been identified as being at risk of loss of biodiversity due to increased

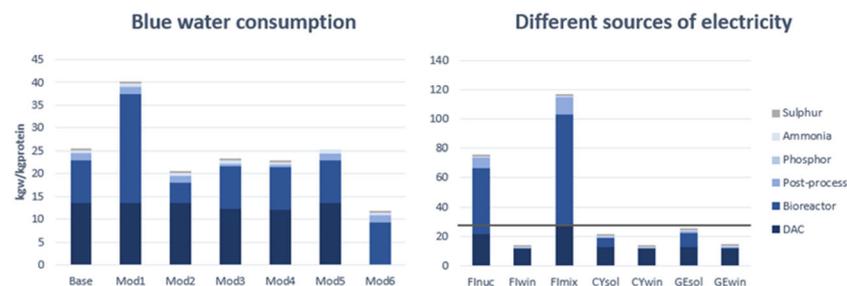


Fig. 5 Blue-water consumption values of PtF systems. Material and energy inputs and outputs of energy production and substance needs are included in the life cycle analysis. PtF applications with different material

sources and technologies (left). The sensitivity of electricity source and location to overall impacts (right). Highlighted horizontal bar shows blue-water consumption value of the reference base setup

Table 2 Environmental impact values of different protein sources

| | GWP [$\text{kg}_{\text{CO}_2\text{-eq}} \text{kg}_{\text{protein}}^{-1}$] | LU [$\text{m}^2 \text{a} \text{kg}_{\text{protein}}^{-1}$] | Water use [$\text{kg}_{\text{water}} \text{kg}_{\text{protein}}^{-1}$] | Eutrophication [$\text{kg}_{\text{P-eq}} \text{kg}_{\text{protein}}^{-1}$] |
|-------------------------|---|--|--|--|
| MP _{PtF wind} | 0.81 | 0.029 | 1.01 | 0.00033 |
| MP _{PtF solar} | 1.00 | 0.060 | 3.75 | 0.00039 |
| MP _{Methane} | 2.23 ^a | 0 ^a | 10 ^a | - |
| Mycoprotein | 15-38.4 ^{bc} | 2.6-7.5 ^{bc} | - | - |
| Soybean | 0.89-3.74 ^{de} | 5.24-6.04 ^d | 6.3 ^f | 0.016 ^g |

^a Cumberlege et al. (2016), ^b Head et al. (2011), ^c Smetana et al. (2015), ^d da Silva et al. (2010), ^e Adom et al. (2012), ^f Mekonnen and Hoekstra (2012), ^g Jekeyinfa et al. (2013)

pressures from soy production (WWF 2014). Future research is needed on how PtF for MP affects biodiversity and its potential to free land from crop production for other purposes, for example, as carbon sinks by afforestation.

When utilizing nutrients from waste flows, as suggested, for example, by Matassa et al. (2015) and Matassa_a et al. (2016), questions remain regarding safety aspects of product sterility (Ritala et al. 2017). However, according to results gained from LCA, using wastewaters as P and S sources causes only a small reduction in the studied impact categories, and thus, there is no significant environmental benefit gained by using wastewaters. In the case of the ammonia or ammoniac source, most of today's NH_3 is produced with the Haber-Bosch process using natural gas as an energy source and to provide H_2 to the process. Thus, only NH_3 from natural gas was considered in this study. Current practice for NH_3 production is fossil dependent and has high environmental impact (Udvardi et al. 2015). However, it is possible to produce NH_3 by supplying H_2 using alternative technologies, which may reduce the environmental impacts of NH_3 production (e.g., Murakami et al. 2005). For example, ammonium sulfate can be recovered from biogas digestate at the sanitation phase. The process has lower systemic energy cost than NH_3 production with the Haber-Bosch process (Törnwall et al. 2017). NH_3 can also be recovered directly from the biogas digester through a semi-permeable membrane, which not only produces ammonia but also improves the digester efficiency (Lauterböck et al. 2014). In view of these alternative NH_3 production methods, the possibility of reducing the impacts of PtF by using novel production practices for NH_3 supply should be investigated.

Electricity generation and the unit process consuming most of the electricity, i.e. the bioreactor with electrolysis, have a major effect on the studied environmental impacts. Thus, for the PtF application to be more sustainable than other comparable protein sources, the source of electricity should be chosen carefully. For example, FImix using the grid mix in Finland as an electricity source for the PtF application causes higher GWP, land occupation, and blue-water consumption values than soybean production, even though a major part of the Finnish grid mix consists of renewables and nuclear

energy. As regards the electricity-to-biomass efficiency of the bioreactor, the use of external water electrolysis can result in lower energy consumption than using in situ electrolysis, but there are safety aspects that need to be considered. For example, the gases fed to the reactor may ignite, when they are in contact with measurement instruments in the bioreactor, causing an explosion (C&EN 2016). In addition to the electricity source and bioreactor efficiency, the source of CO_2 has a pronounced effect on the overall sustainability of the PtF process. If there are no reasonable point sources of pure CO_2 , using DAC can be beneficial. DAC can separate water from air, making the process produce more water than it consumes. Water separation could be advantageous in areas having high water demand. However, using DAC increases the environmental impacts by approximately 10% as the unit process consumes energy and amines. Nevertheless, a PtF setup with a DAC unit process may have less environmental impact than other sources of protein.

Different PtX applications are usually energy-intensive technologies (Koj et al. 2019; Sternberg and Bardow 2015) and PtF is not an exception. It could be argued that the PtX technologies with the least environmental impacts and the least energy-consuming solutions should be preferred to limit the increase of energy demand (e.g. Sternberg and Bardow 2015). However, there are several aspects that should also be considered. For instance, what products from PtX technologies should replace and what different kinds of environmental impacts should be considered, when making the choices. In the case of protein from PtF technology, there are several impact categories that are relevant in the agricultural sector. Land use, water use, fertilizers use, and biodiversity related impacts can each be the most important impact category depending on what product and where the product is produced. Another aspect is that is the limit of possible renewable energy an issue. It is known that the potential of renewables exceeds many times the energy needs of humankind; thus, it is theoretically possible to construct 100% renewable energy systems (e.g., Barbosa et al. 2017; Connolly et al. 2016).

Electricity consumption in MP production via the PtF approach is higher than in soybean production. However, the trend of the price of renewable energy is falling and

production of bacterial MP could be balanced according to the varying production and load of the grid, leading to reduced electricity costs, and/or incentive payments (Zehir et al. 2016). A possible future increase in the cost of food might transform production costs in favor of MP production. Thus, a topic of great interest would be to research the critical tipping point for the economic feasibility of PtF for MP production. Such research should also include techno-economic assessment to establish the best economical setup of PtF application in different locations.

5 Conclusions

The PtF process can be designed so that it causes significantly lower environmental impacts in all the studied categories than most of the other studied protein sources. Major environmental benefits can be gained from substituting conventional protein sources with MP produced via PtF technology. In particular, the land occupation indicator is minimal compared to soybean production, which brings the possibility of converting land currently used for crop production to other purposes, for instance, with afforestation, which can be used for carbon sinks and to tackle biodiversity losses. However, the environmental sustainability of PtF depends greatly on the electricity source used and the electricity-to-biomass efficiency of the bioreactor. In addition, before PtF technology is commercially feasible, techno-economic assessment should be done and larger production capacity reactors should be piloted. Overall, it can be concluded that producing MP via a PtF process has the potential to reduce the environmental burden of agriculture and play a role in mitigation and adaptation to climate change.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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