INTRODUCTION

Microalgae are considered a promising source of fuel as they represent a diverse group of single-cell photosynthetic organisms that grow rapidly in a wide range of habitats. In contrast to traditional crops, they can be cultivated in technical systems on marginal land with nutrient- and CO₂-rich waste (water) streams (Pulz & Gross, 2004; Rösch & Maga, 2012). They have an outstanding photosynthetic efficiency and biomass productivity and can have high contents of fatty acids, polysaccharides, and proteins depending on species and cultivation conditions (Becker, 2007; Spolaore, Joannis-Cassan, Duran, & Isambert, 2006). Some algae species contain up to 40% fatty acids and high amounts of polysaccharides, which can be converted easily into diesel, jet fuel, and ethanol. Because of these advantages and since they do not have the drawbacks of first-generation biofuels, such as land use competition, loss of biodiversity, and environmental pollution through pesticides and fertilizers, and of second-generation biofuels, such as straw or forest residues (Haase, Rösch, & Ketzer, 2016), algae fuels are classified as third-generation biofuels.

Government and private investments in various countries and at different scales have launched pilot-scale programs to develop third-generation biofuel production from microalgae. In the United States, some companies such as Solazyme, Sapphire Energy, and Algenol started to produce diesel and jet fuel, ethanol, and gasoline from algae at a commercial scale (Wesoff, 2017). Most efforts, however, have been abandoned due to the lack of economic viability. Some algae fuel companies have gone bankrupt, while others have adopted new business plans and moved on to high-value markets such as cosmetic supplements, nutraceuticals, pet food additives, pigments, and speciality oils (Wesoff, 2017). These changes indicate that algae technology developed for fuel production can also be used for food production and vice versa. This is due to microalgae’s ability to produce a variety of (high-value) food compounds, such as carotenoids and polyunsaturated fatty acids (PUFAs), and bioactive compounds, such as pigments, vitamins, and enzymes (Chew et al., 2017; Draaisma et al., 2013; Matos, Cardoso, Bandarra, & Afonso, 2017; Milledge, 2011; Wijffels & Barbosa, 2010; Wijffels, Barbosa, & Eppink, 2010; Williams & Laurens, 2010).
these products have beneficial nutritional qualities and health claims, they can achieve high sales prices, which ensure return on investment in algae technology (Enzing, Ploeg, Barbosa, & Sijtsma, 2014; Vigani et al., 2015).

In this paper, the chances and challenges of integrated food and fuel production from microalgae are outlined and discussed based on the results of the microalgae research network funded by the state of Baden-Württemberg, Germany. First, algae species and cultivation, harvesting, and extraction technologies are discussed. The next sections are devoted to economic and environmental aspects. The last section deals with public perception, because consumer acceptance is essential for exploiting the potential of microalgae. Since algae species and their cultivation are similar for food and fuel production, it is expected that only minor changes in the upstream process are required to switch from fuel to food and fuel production. The downstream process, however, becomes more complex in order to valorize different algae compounds for the food and fuel market (see Figure 1).

2 | MICROALGAE SPECIES

The diversity of microalgae in oceans, brackish, and freshwater is vast and promising (Fehling, Stoecker, & Baldauf, 2007; Massana, Terrado, Forn, Lovejoy, & Pedrós-Alió, 2006; Stern et al., 2010) and has been estimated to include anything from 30,000 to more than 1 million species (Guiry, 2012; Richmond, 2004). The broad range is due to uncertainties regarding what organisms should be included as algae and what a species is in the context of various algal phyla and classes. Part of the diversity was screened by the Aquatic Species Program (1980 to 1996) supported by the US Department of Energy to identify promising species, technologies, and processes to produce oil from microalgae. Of this diversity, only few species have been used for fuel production or have commercial relevance for (health) food production (Lee, 1997; Liang, Sarkany, & Cui, 2009; Pulz & Gross, 2004).

*Nannochloropsis* sp., *Neochloris oleoabundans*, *Scenedesmus obliquus*, and *Dunaliella tertiolecta* have been considered as promising candidates for fuel production in terms of quantity and quality of fatty acids (Gouveia & Oliveira, 2009). Some of them show an increase in oil quantity (~50%) when grown under nitrogen shortage. The algae food market is dominated by *Chlorella vulgaris* and *Arthrospira platensis* and extracts of *Dunaliella salina* (β-Carotene), *Haematococcus pluvialis* (astaxanthin) or *Crypthecodinium cohnii* (docosahexaenoic acid) due to commercial factors, market demand, specific preparation, and food safety regulations of the European Food Safety Authority (Chacón-Lee & González-Mariño, 2010). Besides, they have a positive public perception as they are recognized as a natural source of a healthy diet that can prevent health problems of modern lifestyle such as obesity, heart diseases, and diabetics. Table 1 shows the fatty acid, protein, and carbohydrate content (under optimal, N-/P-replete cultivation conditions) of the above-mentioned and other microalgae in comparison with traditional oil and protein plants. It can be noticed that, in these three categories, some algae have a

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**Integrated fuel and food production with microalgae**

**Upstream process (cultivation, harvest)**

- Cultivation
  - Inoculum and production in photobioreactors or open ponds
  - Nutrients (N,P), CO₂
- Harvest
  - (e.g., flocculation, dewatering with centrifuge)
- Microalgae paste (10-25% DM)
  - Separation

**Downstream process (biorefinery approach)**

- Drying
  - (freeze drying, spray drying)
- Cell disruption
  - (e.g. ball mill, High-pressure-homogenization, enzymatic lysis, acid/alkaline treatment, pulsed electric fields)
- Cascaded extraction
  - (e.g. super-critical fluid extraction, pressurized fluid extraction, precipitation, membrane filtration)
- Dry algae
  - Food supplements
    - High-value compounds
    - Biodiesel
    - Bioethanol
- Cosmetics, Chemicals
  - Proteins
  - Polysaccharides
- Food and Feed
  - Biogas, HTL, HTG
- Residual biomass
  - Biogas, HTL, HTG

**FIGURE 1** Integrated production of fuel and food with microalgae
similar composition to traditional oil and protein plants such as soybean and rapeseed, which is a first-generation biofuel crop. The chemical composition of some microalgae can vary due to nitrogen or phosphate depletion. As a result, the lipid or carbohydrate content increases, while the amount of proteins decreases.

For fuel production, the composition of fatty acids is relevant. Suitable microalgae provide a high proportion of unsaturated fatty acids (50%–65%, predominantly polar membrane lipids) and a significant content of saturated palmitic acid (C16:0; 17%–40%; Gouveia & Oliveira, 2009). Among the undesirable unsaturated fatty acids, special attention has been given to the linolenic (C18:3) and polyunsaturated (≥4 double bonds) contents, where European Standard EN 14214 (2004) specifies a limit of 12% and 1%, respectively, for quality biodiesel. Not all the oils extracted from microalgae have linolenic and polyunsaturated fatty acid contents within specifications (Gouveia & Oliveira, 2009).

For food production, not only the amount and purity of protein or fatty acids but also their quality and context are important. The media provide conditions for certain protein structures and qualities—a purified powder, denatured protein, or oxidized fatty acid might be of little value for certain applications. The quality of proteins can vary depending on techno-functionality, digestibility, and availability of essential amino acids (EEAs), which humans are unable to biosynthesize. Although tryptophan and lysine are often limiting amino acids, algae are regarded as viable protein source, with an EAA composition that meets the requirements of the Food and Agriculture Organization (FAO) of the United Nations (Volkmann, Imianovsky, Oliveira, & Sant’Anna, 2008).

### TABLE 1 Composition of main biofuel and food sources with microalgae (% dry weight; Spolaore et al., 2006; Becker, 2007; Gouveia, Batista, Sousa, Raymundo, & Bandarra 2008; Chang, Ismail, Yanagita, Esa, & Baharuldin, 2014; Haar, Müller, Bader-Mittermaier, & Eisner, 2014)

| Commodity                  | Protein | Carbohydrates | Lipids/fatty acids |
|----------------------------|---------|---------------|-------------------|
| Animal products and soybeans |         |               |                   |
| Meat                       | 43      | 1             | 34                |
| Egg                        | 47      | 4             | 41                |
| Milk                       | 26      | 38            | 28                |
| Oil palm kernel             | 16–27a  | 6–11a         | 50–70             |
| Rapeseed                   | 14–18a  | 12–15a        | 40–45             |
| Soybeans                   | 37      | 30            | 20                |
| Microalgae                 |         |               |                   |
| *Chlamydomonas reinhardti*  | 48      | 17            | 21                |
| *Chlorella pyrenoidosa*     | 57      | 26            | 2                 |
| *Chlorella vulgaris*        | 51–58   | 12–17         | 14–22             |
| *Dunaliella salina*         | 39–61   | 14–18         | 14–20             |
| *Haematococcus pluvialis*   | 48      | 27            | 15                |
| *Scenedesmus dimorphus*     | 60–71   | 13–16         | 6–7               |
| *Spirulina maxima*          | 46–63   | 8–14          | 4–9               |
| *Spirulina platensis*       | 52      | 15            | 3                 |

*aContent calculated with data of defatted kernels and seeds in Haar et al. (2014) and Chang et al. (2014).*

### 3 | UPSTREAM AND DOWNSTREAM PROCESSES OF FOOD AND FUEL PRODUCTION

Food and fuel production from microalgae can be separated into upstream processes, including cultivation and biomass harvest, and downstream processes (see Figure 1). The main cultivation systems are open pond systems (raceway ponds with paddle wheels) and closed photobioreactors (PBRs), which can both be used for food and fuel production. Open ponds have been well established since the 1950s because of lower investment and operating costs and lower labor intensity. Despite the higher costs, PBRs are of interest because they allow for better control of the cultivation conditions than open systems. In addition, they achieve higher biomass productivities and allow for a more effective prevention of contamination. A large variety of PBRs has been developed (e.g., tubular, flat plate, green wall). They are mainly used for the production of high-value products (Zijffers et al., 2010) or in hybrid cultivation systems to supply high cell density algae to open ponds (Ben-Amotz, 1995). In PBRs, a high surface-to-volume ratio is needed. Sophisticated and complex constructions including a huge number of surfaces are required to provide optimal light intensity for algae cultivation. This
results in a high-energy demand for pumping and mixing to optimize the supply of light, carbon, and nutrients and for maintaining a constant temperature of 20–30°C.

Microalgae can be either autotrophic or heterotrophic, but some photosynthetic algae are mixotrophic, that is, they have the ability to both perform photosynthesis and acquire exogenous organic nutrients. Photoautotrophic microalgae use CO₂ as carbon source and photosynthesis as energy source. Technically produced CO₂, CO₂-rich emission streams, or CO₂ as carbon source and photosynthesis as energy source. Ectogenous organic nutrients. Photoautotrophic microalgae use the ability to both perform photosynthesis and acquire exogenous organic nutrients. Mixotrophic algae have the ability to perform both. Some photosynthetic algae are mixotrophic, that is, they have the ability to both perform photosynthesis and acquire exogenous organic nutrients. Photoautotrophic microalgae use CO₂ as carbon source and photosynthesis as energy source. Technically produced CO₂, CO₂-rich emission streams, or CO₂ as carbon source and photosynthesis as energy source. Ectogenous organic nutrients. Photoautotrophic microalgae use the ability to both perform photosynthesis and acquire exogenous organic nutrients. Mixotrophic algae have the ability to perform both.

Processing is a major technical (and economic) limitation to the integrated production of food and fuel and high-value compounds that is difficult to discuss, since it is highly specific and strongly depends on the desired products. For algae diesel production, fatty acids are extracted from the lyophilized biomass with solvents such as hexane, ethanol (96%), or a hexane–ethanol (96%) mixture. However, also other extraction methods such as ultrasound- and microwave-assisted extraction are suitable. However, more selective solvents and knowledge about process conditions regarding the type of lipophilic compound to be extracted are needed to enable different ways of processing for each compound. Algae fuels are technologically produced in a form akin to existing processes and technologies used for other biofuel feedstock. By transesterification in a multiple-step reaction, the triglycerides are converted to monoglycerides, and these are then converted to esters (biodiesel) and glycerol (by-product).

For protein extraction, it is of great importance to ensure that the process will not have an impact on protein functionality and quality. Protein extraction involves centrifugation, ultrafiltration, precipitation, chromatography techniques (Sari, Mulder, Sanders, & Bruins, 2015), or solvent extraction and fractionation via lyophilization (freeze drying; Brentner, Eckelman, & Zimmerman, 2011). For more complex and integrated extraction of protein and fatty acids, protein extraction should be performed before lipid extraction to avoid impairment of protein quality. Polysaccharides, which are part of the cell walls or accumulated starch remaining from protein and lipid extraction, can be fermented into bioethanol or butanol. The integrated extraction of the desired food and fuel compounds in sufficient amounts and qualities without them damaging each other is considered a critical bottleneck for the integrated approach. Besides, the scalability of integrated production has to be further investigated due to different market sizes and requirements.

4  |  ECONOMIC ASPECTS

The economic aspects of integrated food and fuel production with microalgae are difficult to assess since such a process does not exist yet. Beyond that, hardly any data on commercial algae production for fuel or food are available, and those that exist are based on either laboratory- or pilot-scale data or on assumptions only. Cost assessments found in literature vary widely depending on data and assumptions on, for example, productivity, energy price, and labor costs (Christiansen, Raj Raman, & Anex, 2012; Norsker, Barbosa, Vermuë, & Wijffels, 2011). The variety of calculation methods and
a lack of transparency in system and process design make comparison even more difficult (Acién, Fernández, Magán, & Molina, 2012; Bastiaens, Roy, Thomassen, & Elst, 2017).

As mentioned before, PBRs are characterized by high capital and operational costs, in particular due to high investment, energy, and labor costs (Da Silva & Reis, 2015). The small size of microalgae and the large volumes to be processed are main reasons for the high capital expenditure and energy consumption. The main cost driver is cultivation, but harvesting and dewatering account for at least 3%–15% of the total costs (Fasaei, Bitter, Slegers, & Boxtel, 2018). According to calculations, commercial production requires a significant reduction in production costs by a factor of 10 to 20 for food and 100 for feed and even more for fuels (Bastiaens et al., 2017; Enzing et al., 2014; Vigani et al., 2015). These numbers indicate that fuel production can only become economically feasible in combination with food production in the medium and long term. Besides, an increase in process stability and reliability is necessary to make integrated food and fuel production viable and competitive.

Cost reductions can be achieved by upscaling downstream processes, reducing labor costs through automation, and integrating recycled waste streams for the supply of nutrients (mainly nitrogen and phosphor) and CO2. Increasing biomass productivity through genetic engineering and more efficient PBR systems can also help to reduce production costs. However, the use of waste streams and genetically modified algae (even with CRISPR-Cas) is difficult or impossible for integrated food and fuel production for reasons of quality, image, consumer acceptance, and current regulations.

Cost reductions through increased yields can hardly be realized with the phototrophic approach, since 80 tons DM per hectare and year are considered as maximum productivity that can be achieved with large-scale microalgae cultivation due to bio-technical limitations (Tredici, 2010). This is only possible by heterotrophic cultivation (Liang et al., 2009), an approach (fermentation technology) that is easily scalable and established at commercial scale for bacteria and yeasts. Heterotrophic cultivation involves lower land and investment costs due to a small surface-to-volume ratio, easily soluble and distributable carbon and energy sources, and reduced downstream costs (Da Silva & Reis, 2015). Besides, production is possible throughout the year with consistently high productivity since it is independent of climate conditions (Bumbak, Cook, Zachleder, Hauser, & Kovar, 2011). However, also heterotrophic cultivation is not competitive due to the costs of the organic carbon source, which account for 60%–80% (in case of glucose) of total costs (Yan, Lu, Chen, & Wu, 2011). Less expensive carbon sources such as glycerol and acetate are not promising either due to lower algae biomass productivity (Lowrey, Brooks, & McGinn, 2015; Perez-Garcia & Bashan, 2015). The most important argument against heterotrophic cultivation, however, is the fuel versus food dilemma, which will arise again if edible sugar is used for integrated production with microalgae, since part of the sugar will be used for fuel production.

## 5 | ENVIRONMENTAL ASPECTS

Like any production process, microalgae food and fuel production is linked to resource consumption and environmental impacts such as climate change. The results of life cycle assessment (LCA) studies on microalgae cultivation, mainly performed for fuel production, differ widely. Depending on the data used and assumptions made, for example, on productivity, content of fatty acids, proteins and polysaccharides, and energy requirement, the energy return on investment (EROI) varies from 0.01 to 3.35 (Ketzer, Skarka, & Rösch, 2018; Weiss, 2016). The highest environmental impact on the global warming potential of algae cultivation in PBRs is related to the consumption of energy, especially electricity for mixing, temperature control, as well as—depending on the concept—lighting (Mok & Rösch, 2017; Smetana, Sandmann, Rohn, Pleissner, & Heinz, 2017). These results are also applicable to food production in PBRs.

Life cycle assessment results for (small-scale) protein production from microalgae in Europe show that the environmental impact and resource footprint are higher than that of imported protein concentrate from large-scale soy meal production in South America (Taelman, Meester, Dijk, Silva, & Dewulf, 2015). In terms of land use, emissions from land use change, and ecotoxicity, algae protein provides benefits, for example, in densely populated areas of Europe, as microalgae can be grown on marginal land compared to traditional agriculture (Rösch, Skarka, & Wegerer, 2012; Walsh et al., 2016). To reduce the environmental impact of microalgae production, energy consumption for mixing and CO2-rich flue gas supply must decrease, and the electricity supply must shift from fossil fuels to renewable sources (e.g., PV, biogas, or wind; Beach, Eckelman, Cui, Brentner, & Zimmerman, 2012; Taelman et al., 2015; Weschler, Barr, Harper, & Landis, 2014). It can be expected that the LCA results for algae protein production can be improved by integrated fuel production according to the allocation principle.

Besides energy, water demand is a crucial factor for microalgae production. The water demand is influenced by climate conditions, system design (open pond or closed PBR), harvesting, and cleaning technologies, but also by species (marine or freshwater algae) and the salt and heat tolerance of algae strains (Rösch & Marting Vidaurre, 2018). The freshwater demand can be reduced by marine or salt-tolerant algae and by recycling culture media after biomass separation. Particularly in southern locations with water scarcity during the summer months, the water demand has a significant
impact on the water footprint. For closed PBR systems, however, the water demand/yield ratio is significantly lower than for traditional agricultural crops.

The nutrient requirements (nitrogen, phosphate) for high algal productivity present another environmental challenge (Pate, Klise, & Wu, 2011). Instead of using chemical fertilizers, nutrient supply for cultivation can be sourced from available organic waste streams (e.g., food industry and communities), agricultural activities (e.g., digestate from biogas plants), or wastewater treatment (Shurtz, Wood, & Quinn, 2017; Walsh et al., 2016). However, this is only applicable for fuel production without costly recovery processes. For integrated food and fuel production, this would require changes in European and national regulations and conditions (Walsh et al., 2016). Reducing nutrient demand can also be achieved by closing nutrient cycles through reuse of nutrients after extraction of compounds for food and fuel production (Rösch et al., 2012).

6 | PUBLIC PERCEPTION

Despite large-scale investments and government mandates to expand biofuels development, little is known about how the public thinks about first-, second-, and third-generation biofuels. Public opinion on first-generation biofuels is less favorable due to the food versus fuel debate. Third-generation algae fuels have the advantage of not competing with arable land. However, with an increasing demand for algae food and fuel, also arable land could be used. In this scenario, integrated food and fuel production is expected to meet with greater public approval than fuel production only. As indicated by the results of a European survey focusing on the use of genetically modified algae to improve fuel productivity, a critical factor for public acceptance and willingness to buy even higher priced algae fuels is that algae technology and products fulfill their promises regarding climate change and environmental protection (Rösch & Varela Villarreal, 2018; Varela Villarreal & Rösch, 2017).

With regard to food production from microalgae, there is no evidence of rejection. In contrast, edible insects and cultured meat, which are also considered as alternative protein sources, face the challenge to mimic traditional meat in terms of sensory quality at an affordable price or to overcome rejection (BfR, 2016; Verbeke, Sans, & Loo, 2015). Microalgae food products focus on health aspects and are offered to consumers as superfoods and dietary supplements. Besides the motivation “health and wellness,” Roßmann and Rösch (2018) identified three other key narratives for microalgae food products: microalgae (a) for cheap and unpretentious products, (b) to sustainably feed the world, and (c) for decentralized, regional food supply. According to their Delphi study, respondents believe that microalgae will contribute to tackling climate change and world hunger as well as to integrating local food supply into other production cycles. Roßmann and Rösch (2018) did not identify any concerns about large-scale microalgae production, which is in contrast to the expectation of experts (Meyer & Priefer, 2018, p. 126). The taste characteristics (gourmet food or unpretentiousness) seem to be of minor importance, although in daily life this is the most important criteria for the purchase of food products.

7 | CONCLUSIONS

Considering the high capital costs of building and operating production systems based on microalgae, the environmental challenges, and the sociotechnical risks of algae technology, the potential of microalgae should be fully exploited by using an integrated approach for food and fuel production. This way, algae fuels are expected to create an ever more favorable public perception and acceptance since there will be no land use competition even if microalgae cultivation increases and expands from marginal to arable land. Among the different compounds, protein is the most promising coproduct of fuel production since the market for plant protein is large and the demand cannot be matched by current European production. Other coproducts such as cosmetic supplements, nutraceuticals, pet food additives, and pigments may achieve higher returns on investment, but have only small markets, which would limit coproduction of fuels. With an ever-growing consumer awareness of health and sustainability, it is expected that the attractiveness of algae products as well as the willingness to buy these products despite higher prices will increase if algae keep their promises. From the sociotechnical point of view, it is crucial that algae fuel and food products will meet the expectations of consumers and promises regarding health and sustainability. The high expectations, acceptance, and trust in microalgae provide a good, but not self-evident basis for the development of integrated food and fuel production from microalgae. Excessive promises in terms of health benefits and sustainability briefly attract attention, but bear the risk that public attitudes will change in the long term if the promises cannot be fulfilled. Integrated food and fuel production from microalgae should therefore be developed using the codesign approach to integrate public perceptions and the views, knowledge, and values of citizens and stakeholders at an early stage into the research and innovation process.

ACKNOWLEDGEMENT

The authors gratefully acknowledge financial support by the Bioeconomy Research Program Baden-Württemberg for the research project Interdisciplinary and transdisciplinary
assessment and scenarios of the use of microalgae for nutrition (Short title "Assessment of nutrition with microalgae").

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How to cite this article: Rösch C, Roßmann M, Weickert S. Microalgae for integrated food and fuel production. GCB Bioenergy. 2019;11:326–334. https://doi.org/10.1111/gcbb.12579