

# Biobased value chains for a growing bioeconomy

## 1 | INTRODUCTION

According to the Global Bioeconomy Summit 2018 (GBS2018), the “bioeconomy” is defined as “the production, utilization and conservation of biological resources, including related knowledge, science, technology and innovation, to provide information, products, processes and services across all economic sectors aiming towards a sustainable economy” ([http://gbs2018.com/fileadmin/gbs2018/Downloads/GBS\\_2018\\_Communique.pdf](http://gbs2018.com/fileadmin/gbs2018/Downloads/GBS_2018_Communique.pdf)). The future bioeconomy is expected to drive the transition towards a more sustainable economy by addressing some of the major global challenges of our time, including food security, climate change, and resource scarcity. Up to 50 countries have already developed or are in the course of developing political strategies to support the growth of a sustainable bioeconomy. The bioeconomy is seen as an approach to the operationalization of sustainability. In this context, the development and provision of biobased products and services clearly requires an emphasis on economic, ecological and social impact assessment. This can only be dealt with in a cooperation between experts representing the different perspectives of sustainability. The supply of biobased products and energy can only be sustainable if all steps in the production process, from biomass supply to use, adhere to the major sustainability criteria. This requires thinking in complete value chains. In addition, resource use efficiency can best be achieved when the various process steps in a value chain are harmonized. To give an example: the better biomass quality can be tailored to the needs of the conversion technology, the less energy and material inputs are required and the higher the yields. This approach is also taken up by biorefinery concepts. These strive to make optimal use of the biomass feedstock by exploiting all components in the best possible way to deliver functional and at the same time environmentally benign products and by making maximal use of recycling options.

It was against this backdrop that the theme of this special issue entitled “Biobased value chains for a growing bioeconomy” was designated. Here, we publish 24 papers, most of which were either drawn up as part of the Bioeconomy Research Program Baden-Württemberg or presented by international research partners at the 2nd International Bioeconomy Congress, held at the University of Hohenheim

in September 2017. Both the research program and the congress are supported and financed by the Ministry of Science, Research and the Arts Baden-Württemberg. The research program evolved from the Bioeconomy Research Strategy developed in cooperation with all universities in the German federal state of Baden-Württemberg. As a result, this federal state has progressed to become one of the leading bioeconomy regions in the EU. The program comprises three Research Networks, reflecting Baden-Württemberg's regional strengths and relevancies in the following fields of the bioeconomy: Biogas, Lignocellulose, and Microalgae. Each Research Network is multidisciplinary, covers the complete biobased value chain from biomass production, pretreatment, and conversion, through to the manufacture and marketing of biobased products, and also includes socioeconomic and ecological assessments. Additionally, each of the research networks collaborates with the Competence Network “Modelling of Bioeconomic Systems. Many of the contributions to this special issue stem from young scientists on the Bioeconomy BBW ForWerts Graduate Program affiliated with the Baden-Württemberg Bioeconomy Research Program.

This special issue is divided into three parts: biogas production, lignocellulose-based products, and algae. Each section covers the entire value chain of the respective bioeconomic field and begins with an opinion article on perspectives for that field.

## 2 | BIOGAS SECTION

In Europe, biogas has become a serious alternative to fossil fuels, complementing other renewable energies from wind and sun. Biogas has the advantage that it can be produced decentrally and at locations with a range of site conditions. In a renewable energy mix, biogas can provide energy reliably, especially at times when energy from wind and sun is low. In their opinion paper, Bahrs and Angenendt (2019) discuss the future perspectives of biogas production. Despite the technical innovations and developments of recent decades, production costs of energy from biogas are still too high to be economically viable. For this reason, several options are currently under discussion for the extension of the biogas value chain by integrating the production of materials, such

as building blocks for the chemical industry. This would provide an opportunity to improve the economic performance of existing biogas plants. Another shortcoming of the sustainability of biogas production is the high proportion of feed crops from agricultural land, notably maize, in biogas feedstocks. This is particularly the case in Germany, which has the highest number of on-farm biogas plants in Europe. Mangold, et al. (2019a) discuss alternative biogas crops, taking the perennial C4 grass miscanthus as an example. They conclude that miscanthus delivers similar amounts of biomass per hectare as maize but, due to its perennial character and low input demand, its biomass supply is more environmentally benign. The challenge is dealing with the ensiling and the lower specific methane yield of the lignocellulosic miscanthus biomass. Mangold, Lewandowski, Hartung and Kiesel (2019b) show that ensiling miscanthus biomass is possible and that the specific methane yield can be improved by green harvesting in October. Another advantage of miscanthus over maize is its ability to grow on land with biophysical constraints to food crop production. This is shown in the contribution of Wagner et al. (2019), who performed a Life-Cycle Cost Assessment (LCCA) of biogas production from miscanthus grown on marginal land. The results clearly show that the use of marginal land for the cultivation of miscanthus as a substrate for biogas production can be reasonable from an economic and environmental perspective. However, the economic competitiveness is limited by the biomass yield and the decision to use marginal land needs to be taken on a case-by-case basis considering site-specific conditions such as local biodiversity. Biogas substrate optimization has led to considerable improvements in the efficiency and effectiveness of biogas production. However, progress in biogas technology can also make a significant contribution to the effectiveness and economic competitiveness of biogas plants. Biological hydrogen methanation is discussed as one option for technological progress (Ullrich & Lemmer, 2019). In this process, the CO<sub>2</sub> fraction of biogas serves as a C source for CH<sub>4</sub> formation. Another opportunity for additional higher value products that can improve the economic competitiveness of biogas plants is described in the contribution of Tampio, Blasco, Vainio, Kahala and Rasi (2019) using the example of the production of volatile fatty acids (VFA) as potential platform chemicals. However, the efficiency of VFA extraction needs to be improved before the biogas value chain can be enriched by this type of product extraction. Another approach to improving the economic competitiveness of biogas plants is analyzed by Güsewell, Haerdlein, and Eltrop (2019) in their assessment of “repowering options” for existing biogas plants. Repowering options refers to the modification and optimization of existing biogas plants. This can be done by replacing individual parts (e.g., with more efficient combined heat and power units), by adapting them to new legal regulations (e.g., expansion of

fermentation residue storage facilities), by modifying process conditions (e.g., improved feed management), or by revising the entire plant concept (e.g., from electricity generation to be used on-site to the feeding of biomethane into the grid).

### 3 | LIGNOCELLULOSE AND MODELLING SECTIONS

Lignocellulose is the most abundant biomass on Earth. Due to this abundance, and also its potentially sustainable supply, there has recently been increased interest in lignocellulosic biomass as a promising renewable resource in a growing bioeconomy. In the introductory opinion article to the lignocellulose section, Dahmen, Lewandowski, Zibek, and Weidtmann (2019) discuss future perspectives for integrated lignocellulosic value chains. They present a modular biorefinery concept as one possible prototype for the future, which can be designed for a range of biomass feedstocks and products and at different scales, from on-farm to industrial. It focuses on the production of chemicals and materials as main products and considers bioenergy as a side product of residue streams. The various components of potential lignocellulosic biorefineries are at very different phases of development. Flagship plants exist only for 2nd generation bioethanol production. A few processes currently under development are at pilot scale (TRL 6), for example, the organosolv process; many others are still close to the proof-of-principle level. Dahmen et al. (2019) discuss the results of research performed within the framework of the “Lignocellulose Research Network” and their contribution to the development of potential biorefinery modules. With regard to feedstocks, Dahmen et al. (2019) conclude that perennial biomass crops (PBC) will most likely play an important role in the future regional biomass supply to European biorefineries. The major PBC in Europe are species of the genera *Miscanthus* (miscanthus), *Panicum virgatum* (switchgrass), *Salix* (willow), and *Populus* (poplar). Breeding programs are in place for the most relevant PBC. These exploit the genetic variability and have delivered genotypes at varying levels of advancement (Clifton-Brown et al., 2019; Fabbrini et al., 2019). The optimal integration of biomass production and conversion requires advanced breeding (see e.g., Clifton-Brown et al., 2019) that tailors the biomass to user needs, resulting in improved pretreatment and conversion efficiencies. For lignocellulosic biorefineries, the main requirement is the reduction of pretreatment efforts. Using miscanthus as an example, Schäfer, Sattler, Iqbal, Lewandowski, and Bunzel (2019) show that this can be achieved by selecting genotypes with suitable cell wall composition. This selection helps reduce the recalcitrance of the lignocellulosic biomass and facilitates the desired separation into the components lignin, cellulose, and hemicelluloses. A study by Seibert-Ludwig, Hahn, Hirth, and Zibek

(2019) systematically compared and evaluated different separation methods for miscanthus and poplar wood. It showed that acid-catalyzed organosolv processing resulted in the highest delignification grade and, after enzymatic saccharification, the highest glucose yield for microbial conversion. Rohde et al. (2019) also applied the organosolv process to optimize lignin separation from miscanthus and poplar with bark to obtain different lignin fractions suitable for chemical industry. Primary conversion of lignocellulosic biomass results in various intermediate products, mainly lignin, cellulose, and hemicellulose. Several contributions to this issue describe how these intermediates can be further processed into final products. Schuler, Hornung, Dahmen, and Sauer (2019) illustrate the use of lignin from bark for the production of aromatics by hydrothermal liquefaction. Wang et al. (2019) have developed recombinant *Pseudomonas putida* strains that use hemicellulose-derived pentoses or wheat straw hydrolysate as their sole carbon source. Horlamus et al. (2019) have developed a *Cellvibrio japonicus* strain that can produce rhamnolipids directly from hemicelluloses in a one-step bioconversion process. Hoffmann, Rodriguez Correa, Sautter, Maringolo, and Kruse (2019) have produced carbonaceous powder materials from lignocellulosic biomass and investigated their electrical conductivity for application as electrode materials in energy storage technologies. It is also possible to feed side streams of other lignocellulosic biomass processing units into biorefineries. In this context, Arnold, Moss, Dahmen, Henkel, and Hausmann (2019) evaluated an approach for microbial valorization of bio-oil fractions produced by fast pyrolysis of ash-rich lignocellulosic biomass.

The lignocellulose section concludes with an economic and ecological analysis, Lask, Wagner, Trindade, and Lewandowski (2019) performed a life-cycle assessment (LCA) to determine the environmental impacts of ethanol production from miscanthus. The type of pretreatment applied has a strong influence on the environmental performance. Three case studies were performed for the federal state of Baden-Württemberg that assess the potential biomass supply and impact of introducing PBC on agricultural production. Gillich, Narjes, Krimly, and Lippert (2019) investigated the potential regional supply of the PBC miscanthus and poplar. For this purpose, they assessed farmers' willingness to engage in PBC production and developed related regional supply functions. Petig, Rudi, Angenendt, Schultmann, and Bahrs (2019) present the linkage of an agricultural sector model and an agricultural farm model for the evaluation of the straw-to-energy and the innovative straw-to-chemicals value chains in Baden-Württemberg that takes the spatial distribution and price-sensitive nature of straw supply into account. The results reveal the trade-off between economies of scale in the energy production plants and biorefineries on the one hand and the feedstock supply costs on the other hand. Additionally, farm-modelling scenarios illustrate the effect of

farm specialization and regional differences on straw supply for biomass value chains as well as the effect of high straw prices on crop rotations.

## 4 | MICROALGAE SECTION

Microalgae are a diverse group of single-celled photosynthetic organisms, which can grow rapidly in a wide range of habitats under photoautotrophic conditions and have protein contents of up to 71%. For this reason, they are regarded as a promising vegan source of protein. They also produce other high-value compounds such as polyunsaturated fatty acids (PUFAs), carotenoids, pigments, vitamins, and bioactive compounds. The production of oil and protein using microalgae is considered a promising alternative to the cultivation of traditional oil and protein crops. The main reason is that microalgae can be cultivated in technical systems without the use of arable land. Ideally, these systems work with closed water and nutrient cycles, and make use of waste streams (Rösch, Rossmann, & Weickert, 2019). Although manifold application opportunities are anticipated, current algae production is unfortunately lagging far behind expectations. This is due to high capital and operational costs combined with low productivity. Another key to the success of microalgae products is public perception. In the first contribution to the algae section, Rösch et al. (2019) discuss these and other bottlenecks to the use of microalgae. They present the concept of an integrated production process, similar to a microalgae biorefinery, as an approach to increasing the competitiveness of algae production through their conversion into a variety of materials rather than a single product. On the one hand, the extraction of valuable products from microalgae is a cost- and energy-intensive step in the process chain. On the other hand, it has been shown that cell disruption and fractionation can increase the bioavailability of microalgae nutrients. Derwenskus et al. (2019) demonstrate the efficient extraction of mono- and polyunsaturated fatty acids (PUFA) and carotenoids (76%–86%) from wet microalgae (e.g., *Chlorella vulgaris* and *Phaeodactylum tricornutum*) using pressurized subcritical extraction solvents (ethanol or ethyl acetate at 150°C). This process design would meet the requirements of food and feed applications and is less energy intensive than other processes involving drying of biomass. Wild, Steingäß, and Rodehutschord (2019) analyze options for processing microalgae into protein feed. They show that mechanical cell disruption may not be necessary to make microalgae protein bioavailable to ruminants. However, they do not regard microalgae as a suitable protein source for ruminants as the proportion of protein that is digested in the intestine is low. In addition, for the introduction of new microalgae products on the food market proper evaluation and pre-market authorization processes are required due to the current food regulation.

This issue provides insights into the perspectives of future biogas-, lignocellulose- and algae-based value chains for a growing bioeconomy. It presents options for shaping the production processes and value chains of biobased products and energy. However, it also demonstrates the large research effort still required to achieve a future postfossil economy.

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