A systematic analysis of economic evaluation studies of second-generation biorefineries providing chemicals by applying biotechnological processes

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Abstract: The objective of this review is a global assessment of the economics of second-generation biorefineries, with a focus on the use of food waste and agricultural residues for chemical production by applying biotechnological processes. Analyses are conducted on feedstock and product distribution, applied economic models, and profitability figures for the period 2013–2018. In a study of 163 articles on different biorefinery systems, the production of chemicals is identified as the second major product class, after bioenergy. Bagasse and straw are frequently analyzed second-generation feedstocks. Based on the evaluation of 22 articles, second-generation biorefineries producing chemicals by applying biotechnological processes proves to be economically feasible. On average, both the internal rate of return (IRR) and the return on investment (ROI) are 20% and the payback period (PP) is 6 years. The cost share of feedstock in biorefineries is between 0–50%. The price of the end product and the fermentation yields have the most impact on profitability. The processing of food waste that has industrial and municipal origins appears more economical than the processing of agricultural residues. Scientists, policy makers and entrepreneurs with an appropriate risk tolerance are advised to pay particular attention to municipal food waste and the potential economic production of carboxylic acids. For various economic issues related to biorefineries, dynamic-deterministic models are recommended, which can be extended by a stochastic model. This review provides an initial overview of the economic feasibility of second-generation biorefineries. Further techno-economic analyses are required to produce statistically significant statements on key profitability figures. © 2020 The Authors. Biofuels, Bioproducts, and Biorefining published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Key words: bioeconomy; second-generation biorefineries; bio-based chemicals; economic evaluation; biotechnological processes; fermentation
Introduction

Fossil resources and oil refineries have typically been significant suppliers of energy carriers and chemicals. However, tightening fossil resource reserves have accentuated the need for alternative sources of supply for energy and chemicals.1 One alternative may lie within the bioeconomy, which aspires to exert a minimal impact on the environment. The bioeconomy is defined as the production of biomass and its conversion into value-added products.2–4 Biorefineries are multi-output systems that produce a variety of bio-based products (e.g. fuels and chemicals) originating from different feedstocks (e.g. straw and bakery waste) and applying different conversion processes (e.g. fermentation and pyrolysis).5,6 Due to the high complexity of biorefineries, different classifications exist.3,4,6–9 These concepts were first discussed in the scientific literature,4,7,8 then summarized in position papers from public organizations.3,4,7

Biorefineries can be classified according to technological implementation status (e.g. conventional and advanced, or first- and second-generation), the type of feedstock (e.g. oil crops and lignocellulosic residues), platforms (e.g. syngas and sugar), products (e.g. fuels and chemicals), and conversion processes (e.g. thermochemical and biotechnological).6,7,9 The classifications of the technological implementation status of a biorefinery and type of feedstock are related.10–12 First-generation feedstock comprise oil and sugar-bearing crops, such as soybean and sugarcane, which are generally edible.13,14 They typically demonstrate high product titers due to their high content of fermentable sugars and fatty acids. Their use for energy and chemical production is controversial because of their contribution to high carbon debts, as well as their competition with food production for the necessary land and water resources.15,16

The production of chemicals and energy from non-edible second-generation feedstock such as straw, bakery waste and rotten fruit seems more ecologically efficient.13,17,18 When considering wastes as second-generation feedstock (e.g. waste cooking oil), these have little or no commercial use,19,20 and could be credited with zero or low carbon debts.16,20 The actual carbon debt is carried by the primary product (e.g. fried food). Agricultural residues and food waste, are available in large quantities worldwide. For example, the worldwide production of wheat is approximately 750 million tons,21 and the resulting quantity of straw is approximately 600 million tons. Almost one-third of food produced for human consumption in Europe and North America is wasted, and thus can be used as feedstock for biorefineries.22,23

Nevertheless, complete lifecycle assessment (LCA) studies evaluating the socio-ecological aspects of second-generation biorefineries from cradle to grave should be considered.24 Third-generation biorefineries based on aquatic biomass (e.g. microalgae) have lower technological readiness levels than other biorefinery systems.7 The potential of aquatic biorefineries and their products is not yet fully known.6 The greatest advantage of third-generation biorefineries is their high greenhouse gas abatement potential, due to the CO₂ absorption of the algae,6,13 while one disadvantage is the comparatively high process costs for end products such as fuels or chemicals.6,25

Classification of biorefineries according to products differentiates between energy (e.g. biodiesel and electricity) and materials (e.g. chemicals and feed).4,9 Fuels such as biodiesel and bioethanol have already received research attention.26–28 They are being produced on an industrial scale. However, in the near future, energy will be supplied increasingly by solar, hydro, and wind power.26 On the other hand, the production of chemicals from second-generation feedstock is attracting growing interest in research and industry, due to the high likelihood of their use as sustainable alternatives to their petrochemical counterparts.7,16,29–31

The classification of biorefineries according to biomass conversion process differentiates between physical, chemical, thermochemical, and biotechnological processes.4,7,9 The primary process steps of biorefineries are pretreatment of the biomass, separation of its fractions, conversion into products, and their purification.6 Physical and thermochemical processes are typically applied within the biorefinery route for biomass pretreatment, separation of different fractions and purification of products.6,7 Chemical and biotechnological routes are used to convert pretreated biomass and platforms into products.4,6

Biotechnological processes in which microorganisms convert chemicals via fermentation are gaining increasing importance.32–34 Compared to chemical synthesis, fermentation can provide product conversions under milder conditions, with low temperatures and energy consumption.35,36 In contrast, at present, the production of bio-based chemicals is often more expensive than fossil-based products.37,38 Economic evaluation is therefore necessary during the early developmental phase to guarantee the feasibility of biorefineries. Developmental freedom is greatest during the early stages, and processes can be modified at minimum cost.39

Currently, 224 working biorefineries are registered in Europe,40 and a significant number is based on sugar / starch (63) and oil / fat (64). Twenty-four are wood-based biorefineries, and food waste is processed in 13 biorefineries. Five use non-wood lignocellulose. As such, a vast potential exists for second-generation biorefineries processing food waste and agricultural residues.
Owing to the multitude of biorefinery options, a large number of review articles with different focal points have been published. Many of the reviews focus on biofuels, while a further focus of reviews is the analysis of biorefineries for the production of chemicals. Ecological reviews of biorefineries have been published for first-, second- and third- generation feedstock. Mostly, techno-economic biorefinery trends were discussed, while profitability figures, such as return on investment (ROI) or net present value (NPV) are not analyzed. Reviews of methods for designing and assessing biorefineries have also been published. There is a lack of reviews focusing on the economics of second-generation biorefineries for chemical production through the application of biotechnological processes.

Considering the importance of economic evaluation, mentioned above, and the research gap that has been identified, the objective of this review is to analyze the economic feasibility of second-generation biorefineries. First, the feedstock and product distribution of biorefineries and the publication years of the selected articles are considered as indications of developmental progress. This analysis should provide scientists, policy makers, and entrepreneurs with information on current trends in biorefinery research and development. In particular, promising feedstock and products are highlighted.

The current state of the economic evaluation of second-generation biorefineries is then analyzed, with a focus on articles that consider systems using food waste and agricultural residues for the production of chemicals by applying biotechnological processes. This analysis includes an assessment of the applied economic methods and the key cost and profitability figures. The use of LCA models is also monitored, as holistic assessments should not only consider economic aspects. Finally, the economic feasibility of second-generation biorefineries is assessed and recommendations are formulated. The results provide scientists with a proposal regarding the most suitable economic methods and key figures for evaluating their biorefinery concepts. The results should also guide scientists and developers in the early planning stages, to avoiding errors in the planning of biorefineries.

Methodology

First, the methodology used for the generation of a literature database and the classification of biorefineries are explained. Then the methods used for the analysis of the economics of second-generation biorefineries are presented.

Generation of the literature database and classification of biorefineries

The scientific databases Web of Science Core Collection, ScienceDirect, and Wiley Online Library were selected for the development of a literature database (Fig. 1). The keywords for the search queries were derived from the title of this review, the objectives in the introduction, and the topic of this review: (0) economic, (1) biorefinery, (2) fermentation, (3) waste, (4) food waste, (5) residues, (6) agricultural residues, (7) bioproduct, (8) bio-based, (9) bioprocess and (10) second generation. In the search queries for articles, the keyword ‘economic’ (0) was always used first, followed by another keyword (1–10).

Due to the fast-paced technological progress of second-generation biorefineries and the dynamic economic conditions, the review period should not extend over many years. Published reviews of biorefineries and biofuels demonstrate a greater increase in scientific research on this topic between 2006–2010. The selected period under review for the generation of a literature database was between 2008–2018. Within this period, the keywords ‘economic’ and ‘biorefinery’ were used within the selected three databases to determine the number of articles containing the search terms in their headline, abstract, and text. Beginning with 2018, the 75th quantile of articles was selected. The 75th quantile as a limit for the period under review was agreed internally between the authors of this review, to narrow this period to the most recent publications. In the newly defined period, only articles that contained both chosen keywords (e.g. ‘economic’ and ‘fermentation’) in their headline were selected. After each keyword search, the articles were sorted by relevance into groups of 50 and imported into the literature database. For further analysis, only studies dealing with the economics of biorefineries were included.

The chosen articles were classified according to publication year, feedstock and product. The classification of feedstock and products was based on the guidelines of the Association of German Engineers for the Classification of Biorefineries. Minor modifications were made due to this review’s focus on food waste and agricultural residues for chemicals production: In terms of feedstock, a distinction was made between the classes ‘food waste and agricultural residues’ (FWAR), ‘cultivated crops’ (CC), ‘wood biomass’ (WB) and ‘aquatic biomass’ (AB).

‘Food waste and agricultural residues’ (FWAR) was further classified into ‘agricultural residues’ (AR), ‘industrial food waste’ (IFW) and ‘municipal food waste’ (MFW). Agricultural residues (e.g. straw and slurry) are produced and distributed by farms. Industrial food waste is generated centrally in the
The products were divided into the classes ‘bioenergy carriers’ (e.g. ethanol and methane), ‘chemicals and intermediate products’ (e.g. succinic acid), ‘electricity and heat’, ‘feed’ (e.g. proteins), ‘fertilizers’ (e.g. digestates), ‘materials’ (e.g. activated carbon), and ‘food’ (e.g. sugar). Furthermore, the most frequently investigated chemicals were grouped – for example, alcohol (e.g. butanol), carboxylic acids (e.g. lactic acid), polymers (e.g. lignin) and hydrocarbons (e.g. ethylene). Platforms were reviewed in terms of which subsequent utilization would occur before being allocated to the respective product class (e.g. ‘chemicals and intermediates products’ or ‘bioenergy carriers’).

A final selection was applied to the literature database to evaluate the economic feasibility of second-generation biorefineries. The focus was on biorefineries using FW AR (e.g. straw and waste cooking oil) for the biotechnological production (e.g. fermentation) of chemicals (e.g. succinic acid).

**Analysis methods for the economics of second-generation biorefineries**

The detailed evaluation of studies on the economics of second-generation biorefineries for chemicals production by applying biotechnological processes focuses on two primary topics: (I) methods of analysis, and (II) economic evaluation and feasibility. The proper choice of analysis method is crucial for the evaluation of biorefineries and the processing of food (e.g. bagasse and shrimp shell waste).

Municipal food waste is more heterogeneous and arises, for example, in private households, restaurants, public facilities, and landfills. The delimitation between agricultural residues (e.g. straw) and food waste (e.g. bagasse and rotten fruit) was made from the farm gate, respectively with the processing of agricultural products in a factory.

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The analysis of deterministic economic models includes primarily (Ia) the applied economic model, and (Ib) the source used for data acquisition. In the analysis of the applied economic model, a distinction was made between the time reference (static or dynamic) of the cash flows and the data format (deterministic or stochastic):

- In static economic models, it is assumed that all revenues and costs occur simultaneously. Average costs and revenues are used for calculations.52–54
- In dynamic economic models, the timing of revenues and costs is considered. Early revenues are more favorable than later revenues. Costs are more favorable in the late stages of investment than in the early stages.55–57
- In deterministic economic models, the probabilities of the input variables (e.g. yield and price of chemicals) are known with certainty. An exact result for the profitability of an investment can be calculated.58–60
- In stochastic economic models, the exact occurrence of the input variables is uncertain, and the probability distribution of the output variables must be determined.61–63

In acquiring articles for review, a distinction was made between whether in-house laboratory trials were conducted or literature data was used. Concerning the use of data from laboratory trials, no distinction was made whether the data were published first in the article under review or prior in a separate article. In addition to economic models, the use of LCA was analyzed (e.g. global warming potential). Lifecycle assessment models are a suitable supplement to economic models for determining the overall sustainability of biorefineries.64 Due to the economic focus of this review, only the use of LCA models was identified. Environmental impacts of individual process steps of biorefineries were not examined.

The economic feasibility of second-generation biorefineries for chemicals production was assessed based on their (Ia) cost structure and (I Ib) key profitability figures. Regarding cost structure, feedstock costs and additional cost shares were analyzed. In terms of key profitability figures, the most frequently observed figures in the articles were selected for analysis. Finally, the economic feasibility was derived and recommendations formulated. Monetary inflation was not considered. All cost and profitability figures in this review article were calculated and reported in US$. In the biorefinery studies that were analyzed, a distinction was made between single output systems (SOS) and multi-output systems (MOS). In SOS, only chemicals are produced, while in MOS, other products (e.g. fuel) are produced in addition to chemicals. If the authors of an article examined a large number of scenarios, all were initially checked. However, only the most profitable scenarios were selected; scenarios that the authors consider promising. Nearly identical scenarios, with only small differences in production process, were not evaluated.

Results and discussion

The results of the search queries in the three scientific databases and the literature database generated are analyzed first. Then global developments in economic research on biorefineries are analyzed. Feedstock and product distribution are also analyzed to obtain an overview of the most promising trends. In a detailed analysis, the results of the economic evaluation of second-generation biorefineries are discussed. Finally, the economic feasibility of second-generation biorefineries is derived and recommendations are provided.

Generation of the literature database

In the preselected period, 2008–2018, querying the three scientific databases using the keywords 'economic' and 'biorefinery' generated 7474 results (Fig. 2), and the results indicate a positive increase over time. Of the articles obtained dating from 2008 to 2018, 75% were issued between 2013 and 2018. The second query in the three scientific databases, using the selected combinations of keywords (e.g. 'economic' and 'biorefinery' and 'economic' and 'fermentation' in articles' headline), resulted in 1215 hits. After each query in the three databases, the articles were sorted by relevance and the first 50 selected for the literature database. Articles detected multiple times were only imported into the literature database once, and the 1215 hits consequently resulted in an import of 313 articles. After excluding studies that did not address the economic evaluation of biorefineries, 163 articles remained, only 22 of which dealt directly with the economic analysis of second-generation biorefineries for chemical production by applying biotechnological processes. The small numbers of remaining articles suggest a first research gap of reviews on economic evaluation of biorefineries. Comparable reviews also demonstrate that natural sciences and engineering studies are more present than economic studies.30, 31, 48

Feedstock and product distribution in biorefineries

In the 2013–2018 reporting period, the 163 recorded articles in the literature database are non-linear in time. Most articles are from 2016 (52 articles); the fewest are from 2015 (23 articles). In economic research on FWAR, a linear trend in
the number of publications can be observed in the 2013–2016 period, which ended in 2017. Publication year distributions are more homogeneous at CC, WB, and AB. Most studies analyzed the utilization of FWAR (104 articles) and CC (44 articles). The numbers of studies that analyzed the use of WB (43 articles) and AB (11 articles) are lower (Fig. 3). Bioenergy carriers, electricity, and heat have the largest shares in WB (70%) and FWAR (64%). The production of chemicals and intermediate products is lowest in FWAR (22%) and WB (26%), and highest in AB (42%). Both findings highlighted in this chapter—the positive trend in research on FWAR and the current importance of chemicals and biofuels—can be confirmed by previously published reviews and public statistics.

The three feedstock subclasses AR, IFW, and MFW show a similar trend in terms of number of publications over time: the number of publications almost stagnated between 2013 and 2015, increased between 2016 and 2017, and decreased in 2018 (Fig. 4). Most studies analyzed the utilization of IFW (61 articles), and fewer studies analyzed the processing of AR (46 articles) and MFW (26 articles). In relative terms, the analysis of bioenergy production is highest for AR (75%), and lowest for MFW (56%). The share of analysis of the production of chemicals is highest for IFW (24%) and lowest for AR (14%).

The most studied feedstocks in FWAR are straw and residues from sugar production. Among the feedstock straw, the utilization of corn stover was most analyzed (15 articles), followed by straw from sugarcane, wheat...
The range of different residues from sugar production is small, and the utilization of bagasse from sugarcane (24 articles) and sweet sorghum (four articles) is commonly detected. The composition of MFW is heterogeneous, and its traceability difficult to verify. The utilization of a mix of food leftovers from private households, public institutions or restaurants was often analyzed (16 articles), while more homogeneous feedstocks such as waste cooking oil or bakery waste were less analyzed (five articles).

Regarding the distribution of chemical groups within the four feedstock classes, FWAR has the widest range (eight groups) (Fig. 5). The range of produced chemical groups in WB (seven groups), CC (six groups) and AB (five groups) is smaller. Carboxylic acids account for the largest share of chemical groups produced in FWAR (29%), and CC (33%). In both feedstock classes, lactic acid and succinic acid are the most frequently analyzed carboxylic acids. Polymers form the largest group in WB (38%) and AB (45%). The polymers obtained from WB are mostly lignin. Aquatic biomass is primarily used to produce proteins.

Within FWAR, the distribution of the analyzed chemical groups in the AR subclass is relatively homogeneous (Fig. 6). Alcohols account for the largest share (28%) and butanol is frequently produced. Carboxylic acids, hydrocarbons, and ketones have equal shares in AR (17%). Compared with AR, the distribution of the analyzed chemical groups is more heterogeneous in IFW and MFW. In IFW, alcohols (30%) and...
carboxylic acids (27%) have the highest shares. Glycerol and succinic acid are frequently analyzed chemicals. In MFW, carboxylic acid (40%) accounts for the largest share, and lactic acid is often analyzed.

The allocation of platforms to the previously defined product classes was quite difficult to perform. As explained in the methods section, no additional classification was conducted for platforms. According to common classifications guidelines, lignin is a platform. For instance, the platform lignin can be converted to chemicals or burned for energy production. Furthermore, platform proteins from algae can also be used as food for humans or feed for animal nutrition. The classification of these mentioned intermediates as ‘bioenergy carriers’, ‘food’ or ‘feed’ would, for example, reduce the number of chemicals, particularly polymers, observed in WB and AB.

Economic evaluation of second-generation biorefineries

For the economic evaluation of second-generation biorefineries, 22 articles were selected from the literature database (Table 1). These articles present the results of economic analysis of second-generation biorefineries that focus on the production of chemicals by applying biotechnological processes. The distribution of feedstock classes in the 22 articles resembles their distribution in the entire literature database. The highest percentages are for straw (32%), residues from sugar production (27%), and waste from municipal origins (14%). The distributions of chemicals and intermediates are more heterogeneous, with carboxylic acids accounting for the highest share (64%). A large number of the studies investigate MOS (77%). Within the MOS, electricity and heat (33%), feed (30%), and bioenergy carriers (26%) comprise the highest shares.

Applied methods

Three of the four pre-defined economic models, which differ either in time reference (static or dynamic) or data format (deterministic or stochastic), were recorded in the 22 selected studies (Fig. 7). The dynamic-deterministic models (45%) and the static deterministic-models (36%) comprised the most significant shares. Stochastic models were applied less frequently for economic calculations (18%). The primary data sources for the 22 studies were in-house laboratory trials (64%). To a lesser extent, data sources were based solely on literature reviews (36%). None of the studies was based on data from industrial or pilot-scale production, which indicates the early developmental stage of second-generation biorefineries. It can also be assumed that biorefinery concepts that have reached a commercial level will not be published, to protect investors’ interests. Six of the 22 studies solely analyze the provision of chemicals. All six used in-house laboratory data. In the SOS, more static models than dynamic models were applied. For the studies on MOS, dynamic models were applied more often than static models. Stochastic models were only used in the analysis of MOS, when the data source was primarily based on literature reviews.

Ecological figures were calculated in seven of the 22 studies, in addition to financial data. Four studies included a more comprehensive LCA with three or more impact categories, for example acidification potential, ozone depletion potential, and global-warming potential.
One study contained only an energy balance, and one study included the global warming potential of a biorefinery. No study considered social aspects of the evaluation of biorefineries comprehensively. However, one study analyzed the effects of different labor capacities for job creation on the cost structure of a biorefinery. The LCA studies were mostly considered for MOS studies whose data sources were based on literature reviews, whereas SOS studies often used a static-deterministic model without LCA, and the data were frequently based on in-house laboratory trials.

The determination of the biorefinery system (SOS or MOS), the applied economic model (e.g. static-deterministic or dynamic-deterministic), and the primary data sources was not always unambiguous. For instance, if internal laboratory data were used, they could have been published either in the current reviewed article or in a previous article. Furthermore, the data used for the analysis were never entirely based on in-house laboratory trials. However, the data for the modeling of the fermentation processes were often based on laboratory experiments.

### Cost structure

In this review, six distinct cost items with significant contributions to total process costs were determined for the analysis of cost distribution in biorefineries: (1) feedstocks, (2) raw materials, (3) labor, (4) utilities, (5) consumables, and (6) depreciation (Fig. 8). Feedstocks refer to FWAR, while raw materials include any other substances (auxiliaries and additives) used for pretreatment, fermentation, and purification. The cost proportions of the feedstock subclasses AR, IFW, and MFW in the overall costs of biorefineries were analyzed separately (Fig. 9). Results from 17 studies were considered for the analysis of the cost structures.

The ranges of feedstock costs for both SOS and MOS are high (0–50%), and the arithmetic mean is approximately

| References | FWAR                  | Chemicals and intermediate products from FWAR | Additional products from FWAR |
|------------|-----------------------|-----------------------------------------------|-------------------------------|
| I          | Potato juice and sugar beet molasses | Propionic acid                              | -                             |
| II         | Corn husk              | Butyric acid                                  | -                             |
| III        | Soy molasses           | Propionic acid                                | -                             |
| IV         | Soy molasses           | Polymeric acid                                | -                             |
| V          | Shrimp shell waste      | Chitosan                                      | -                             |
| VI         | Bagasse                | Succinic acid                                 | Electricity                   |
| VII        | Bagasse and straw       | Itaconic acid                                 | Electricity                   |
| VIII       | Straw, bagasse and husks | Propanediol, succinic acid, lactic acid         | Bioenergy carrier             |
| IX         | Corn stover            | Cresol, catechol, acetic acid, formic acid, phenol, sulfuric acid, furfural, acetaldehyde | Bioenergy carrier, electricity |
| X          | Corn stover and bagasse | Butanediol, hexanoic acid                      | Bioenergy carrier             |
| XI         | Straw and bagasse       | Propylene                                     | Electricity and heat          |
| XII        | Straw                   | Ethanol, propanol, butanol, pentanol, succinic acid, polyactic acid | Electricity, feed, materials |
| XIII       | Bagasse and molasses    | Polyhydroxybutyrate                           | Electricity, feed, fertilizer |
| XIV        | Comcub and coffee silverskin | Fructooligosaccharides                      | Feed                          |
| XV         | Organic municipal solid waste | Volatile fatty acids                       | Bioenergy carrier, fertilizer |
| XVI        | Municipal food waste    | Lactic acid, plasticizer                      | Feed                          |
| XVII       | Banana peel             | Xylitol                                       | Bioenergy carrier, electricity and heat |
| XVIII      | Food waste powder       | Lactic acid, polyactic acid, lactide lipids   | Feed                          |
| XIX        | Bakery waste            | Succinic acid                                 | Feed                          |
| X          | Olive pits              | Xylitol, polyhydroxybutyrate, furfural         | Bioenergy carrier, electricity |
| XXI        | Brewery waste           | Xylitol, lactic acid, phenolic acid           | Materials, feed               |
| XXII       | Slaughterhouse waste    | Polyhydroxyalkanoates                         | Bioenergy carrier, electricity and heat, feed |
equal for both systems. In general, low costs can be expected when MFW is utilized.\textsuperscript{18, 54, 57, 58} The use of MFW could even add to revenues.\textsuperscript{18, 57, 58} Revenue was generated from the sourcing of feedstock if, for example, service fees were charged for the collection of private or public food waste. Feedstock costs tend to be higher when AR are processed.\textsuperscript{56, 61} The cost shares of IFW are, on average, between the cost shares of AR and MFW.\textsuperscript{17, 76}

For SOS, feedstock costs for the processing of soy molasses are above average.\textsuperscript{53, 73} Above-average feedstock costs at MOS are associated with the valorization of bagasse and corn stover.\textsuperscript{56, 63} One reason for high feedstock costs are logistics costs. Transportation expenses are often neglected in biorefinery system calculations,\textsuperscript{17, 53, 73} but these expenses are particularly relevant when the feedstock used originates from different geographical areas.\textsuperscript{56} On the other hand, transport costs of waste from food production sites to a biorefinery can be financed by a third party.\textsuperscript{57}

Raw materials are crucial for both SOS and MOS.\textsuperscript{17, 18, 57, 59, 72} A significant cost driver is, for instance, sodium hydroxide used to adjust pH during fermentation.\textsuperscript{59, 72} Electrodialysis techniques, in combination with bipolar membranes, could reduce the cost of sodium hydroxide but increase costs at other process stages.\textsuperscript{72} As lignocellulose does not always provide sufficient carbohydrates for microorganisms, the complementary supply of glucose or glycerol can be an
Additional primary cost driver.\textsuperscript{18, 72} Additional cost drivers are chemicals (e.g. CaO, K\textsubscript{2}HPO\textsubscript{4} and H\textsubscript{2}SO\textsubscript{4}) for liquor detoxification of pretreated biomass or fermentation media compositions.\textsuperscript{17}

The highest costs for SOS are related to the depreciation of investments.\textsuperscript{59, 72, 73} The depreciation costs of MOS are comparatively low and can likely be explained by the higher number of products produced.\textsuperscript{56, 60, 76} Plant components, such as that for the pretreatment (e.g. hydrolysis) of residual materials, must be installed once in MOS. Follow-up investments in first-generation biorefineries for processing second-generation feedstock often generated low additional costs.\textsuperscript{14, 17, 63} Conversely, follow-up investments in components for the further processing of intermediates into other chemicals can generate comparatively high additional costs.\textsuperscript{63} In particular, it was not possible to determine whether the use of a specific feedstock or the provision of a specific product influenced the level of depreciation costs.

Utility costs have a comparatively high variance for MOS and comprise significant cost factors in some studies.\textsuperscript{12, 60} This variance can be attributed to the different conversion processes used for each biorefinery and their associated energy demands.\textsuperscript{57, 60} Heating and cooling costs can account for a substantial portion of utility costs.\textsuperscript{60} The integration of different products and the sequentialization of process steps could save energy, and thus utility expenditure.\textsuperscript{12} An analysis of varying mass and energy integration levels suggests that energy integration has a greater impact on economic scope than does mass integration.\textsuperscript{60}

Both SOS and MOS labor costs account for a minor share of the overall costs of biorefineries.\textsuperscript{12, 59, 63, 72} In some cases, expanding labor capacity has a tolerable impact on costs and could thus be a good solution for job creation in some areas.\textsuperscript{12} Consumables account for the lowest share of total costs for both SOS and MOS.\textsuperscript{53}

Due to the low availability of data on some cost items and the diversity of analyzed biorefineries, no statistically significant connections could be derived. The structuring of the cost items of the selected 22 articles and the compilation for this review were not always obvious. In some articles, the cost items were classified similarly to the selected cost items of this review.\textsuperscript{53, 73} Additional cost items were identified in articles, but their allocation to the cost items in this review was rarely possible (e.g. plant overhead and land rent).\textsuperscript{55, 58–60} Furthermore, a differentiation between feedstock costs and raw material costs was often not feasible because biogenic residues and auxiliaries and additives were combined into the cost item raw materials.\textsuperscript{12, 55, 60} Feedstock costs of whole-crop biorefineries, which process first- and second-generation feedstocks, were also difficult to allocate to FW AR.\textsuperscript{17, 63}

Profitability

The net present value (NPV), internal rate of return (IRR), return on investment (ROI), and payback period (PP) are the most frequently calculated economic key figures in the 22 articles and have thus been chosen for assessing the overall economic feasibility of biorefineries. For SOS, two scenarios from one single study have NPV data, whereas in MOS, 13 scenarios from seven studies have NPV data. The NPV for SOS ranges from 0.48 to 0.50 million US$. For MOS, the range is 2.58 to 235 million US$. Both comparatively high and comparatively low NPVs are calculated for MOS when MFW is used (2.58–235 million US$).\textsuperscript{57, 58}
In the reviewed MOS studies, the sale of bioenergy carriers and feed is often considered, which increases the overall revenue of biorefineries.\textsuperscript{14, 57, 58, 61} The share of bioenergy carriers in the overall revenues is comparatively high if ethanol and jet fuel are the main products and chemicals are by-products.\textsuperscript{14, 55, 61} An increase in revenues can also be achieved if credit is provided for the utilization of MFW.\textsuperscript{18, 57, 58} Revenues were generated from the sourcing of feedstock, e.g., by charging service fees for the collection of private or public food waste. Furthermore, additional revenues could be obtained in lignocellulose biorefineries if lignin is converted into chemicals.\textsuperscript{61} Currently lignin is usually burned to provide process energy.

In this review, the key figures IRR, ROI, and PP are positively correlated. Regarding the IRR, two scenarios from one study provide data for SOS, and 13 scenarios from eight studies for MOS. For the ROI, two scenarios from two studies generate data for SOS, and six scenarios from four studies for MOS (Fig. 10). In terms of PP, four scenarios from three studies provide data for SOS, and six scenarios from four studies for MOS (Fig. 11). On average, the IRR is higher and the PP lower for SOS than for MOS.\textsuperscript{53, 59} Conversely, the ROI, is on average, higher for MOS than for SOS.\textsuperscript{58, 75} If the variances of the analyzed systems are considered, MOS potentially offers higher economic efficiency than SOS.

The profitability figures for the three feedstock subclasses AR, IFW, and MFW show only marginal differences (Fig. 12). In general, no correlation could be identified between the cost share of FWAR and the three analyzed profitability figures (IRR, ROI, and PP). The mean IRR is highest in the utilization of MFW, and lowest in the processing of AR. In terms of ROI and PP, the processing of IFW is on average more profitable than the processing of MFW (Fig. 13). For the feedstock subclass AR, no data were available for ROI or PP.

Most of the studies demonstrate that end-product prices impact profitability most.\textsuperscript{17, 18, 57, 58} Additional sensitive factors for profitability are yields from fermentation processes,\textsuperscript{14, 54, 61, 66} raw material costs,\textsuperscript{14, 57, 58} and fixed capital costs.\textsuperscript{54, 58, 61, 66} The economic risk of investing in additional equipment to expand the product range is estimated to be either lower or higher,\textsuperscript{14, 17, 61, 63} Economic risk appears lower if there is little investment in additional equipment, and if second-generation feedstock is processed in addition to first-generation feedstock.\textsuperscript{14, 17, 63}

**Economic feasibility and recommendations**

Based on the positive trend identified in economic research on FWAR in this review and the high quantities of food waste available worldwide,\textsuperscript{22, 23} the trend of research activity in this area is expected to continue. In particular, it is expected that the trend of research on IFW will increase more rapidly than the trend of research on AR. Agricultural residues show a comparatively strong decrease in the number of publications in the years 2016–2018, and it is further assumed that AR has other higher opportunity benefits than utilization in biorefineries. The incorporation of AR such as straw into the ground is important for soil fertility,\textsuperscript{78, 79} and straw as bedding for livestock is an important factor for animal welfare.\textsuperscript{80}

Based on the profitability evaluation, processing of IFW and MFW also demonstrates slightly higher economic efficiency than processing of AR.\textsuperscript{14, 58, 59, 75} The economic advantage
of IFW and in particular MFW is primarily low feedstock prices,\textsuperscript{18, 57–59} which could lead to high economic efficiency.\textsuperscript{58, 59} However, prices could rise if the demand for IFW and MFW increases. In conjunction with the state of research on FWAR discussed above, investments in IFW biorefineries seem to have the better reward–risk ratio than MFW and AR biorefineries. It should be noted, however, that the statements on the economic feasibility of MFW are based on a few nearly identical studies.\textsuperscript{18, 54, 57, 58} Natural scientists and economists are therefore recommended to increase research efforts on MFW, to expand the database of techno-economic analyses.

The analyses of the cost structure of different FWAR biorefineries indicate that the cost items feedstocks, depreciation, and raw materials can account for a major share of the overall costs. Scientists, developers and entrepreneurs are advised to provide adequate calculations of these cost items when planning their own biorefinery concepts.

In particular, the logistics chain has a crucial influence on feedstock costs,\textsuperscript{14, 16, 56, 77} and should be adequately considered.

Industrial food waste and MFW may have a high water content, which can degrade the storability and transportability of the feedstock.\textsuperscript{16, 81} The availability of AR is seasonal,\textsuperscript{57} which increases the challenges for logistics and storage. Industrial food waste and MFW can be located in urban areas or close to large-scale food processors or municipal dumps,\textsuperscript{18, 57–59} whereas AR such as straw are located on agricultural land.

Investment in MOS instead of SOS reduces the share of depreciation in the overall cost structure and increases revenues and net present value.\textsuperscript{14, 55, 58} Investment costs stagnate for certain pretreatment equipment, while revenue increases due to the provision of further products.\textsuperscript{17, 54, 55} Economic risk could increase if innovative technology is needed to process second-generation
feedstocks into chemicals and fuels.\textsuperscript{14, 61, 63} Only entrepreneurs with long-term perspectives and appropriate risk tolerance could therefore invest in MOS that process solely FWAR.

With regard to the chemicals produced in the articles on the economics of second-generation biorefineries, no clear recommendation can be given. However, sensitivity analyses demonstrate that variations in fermentation yields of chemicals have a major impact on profitability.\textsuperscript{54, 61, 62, 66} Due to the wide variety of studies analyzed in this review, a target value cannot be given. The scenarios analyzed from the selected articles demonstrate a wide range of chemicals that are economically viable.\textsuperscript{14, 55, 58, 61, 75} Due to the higher frequency of economic studies on carboxylic acids, in particular succinic acid and lactic acid,\textsuperscript{14, 17, 57, 58, 74} growing interest and increased technological development seem evident for these chemicals.\textsuperscript{38, 62, 82}

In this review, three economic models were identified. Depending on the objective, different economic models can be used for the evaluation of biorefineries.\textsuperscript{14, 24, 52, 58} Static-deterministic models are recommended for early stage SOS analysis when scientists prioritize analyzing process kinetics.\textsuperscript{52, 73} These are less complex and allow quick analysis to determine critical parameters. Dynamic-stochastic models have a higher level of complexity and are more suitable for strategic planning of late-stage biorefineries, when scientists, developers or entrepreneurs wish to evaluate the entire process chain.\textsuperscript{14, 51, 63, 83}

In certain cases, stochastic models could be appropriate for the evaluation of early stage biorefineries, as prices and yields of products, as well as plant costs, are often uncertain.\textsuperscript{14, 17, 61, 63} However, the need for data and the knowledge of the timing of revenues and costs are crucial, and the probabilities of the input parameters must be estimated well.\textsuperscript{31, 81} If corresponding distribution functions of input parameters are not available, then simply structured sensitivity analyses are more suitable.

In addition to economic models, LCA are recommended for sustainability analysis of biorefineries.\textsuperscript{24, 48} Current political discussions on climate change and carbon taxes justify a stronger inclusion of LCA and environmental issues in economic studies.\textsuperscript{84, 85} Holistic analyses of processes should not only consider economic aspects.\textsuperscript{24} The additional effort is comparatively low because the same energy and mass flows must be collected for both economic evaluation and ecological balancing.\textsuperscript{25} Although in this review, LCA was identified more in the analysis of late-stage MOS,\textsuperscript{55, 75, 76} ecological balancing can also be recommended for the analysis of SOS to identify ecological inefficiencies even at an early stage of development.\textsuperscript{24, 72}

**Conclusion**

Overall, the review outlined the economic potential of food waste and agricultural residues as feedstock for biorefineries for the production of chemicals by applying biotechnological processes. In terms of progress, the economic evaluation of food waste and agricultural residues indicates a clearer positive trend over the period under review (2013–2018) than other observed feedstocks (e.g., cultivated crops and wood biomass). There are currently more economic studies focusing on the use of industrial food waste than economic studies focusing on agricultural residues or municipal food waste. In particular, straw and bagasse were often economically analyzed feedstocks. Apart from the production of bioenergy, the economic evaluation of chemicals was frequently analyzed. Economic research has often focused on the evaluation of carboxylic acids, particularly lactic and succinic acid.

In addition to the trend analysis of different feedstocks and products, this review provided analyses of the economic evaluation of second-generation biorefineries for chemical production using biotechnological processes. The profitability of the biorefineries from the selected studies was often evaluated with a dynamic-deterministic model. When modeling process kinetics, authors often used results from in-house laboratory trials.

As observed in this review, slightly higher economic efficiency can be achieved in the processing of food waste from industrial and municipal origin than in the processing of agricultural residues. One reason might be the lower feedstock costs of food waste. These are particularly low when the waste has municipal origins. In terms of feedstock costs, logistics of feedstock is a key factor. Prices for end products and fermentation yields in chemical production, as well as high investment and raw material costs, are identified as further crucial factors for the profitability of second-generation biorefineries. Market prices of chemicals cannot be influenced, while fermentation yields of chemicals can be increased by additional research efforts. In single-product biorefineries, investment costs are high in proportion to overall costs, but expenses already incurred for plant components, such as for pretreatment of biomass, can be allocated proportionately to more products if the range is expanded. Scale effects could also reduce investment costs if practical implementations of biorefineries increased.

This review considered the profitability and feasibility of second-generation biorefineries, targeting different groups (scientists, policy makers, developers and entrepreneurs). Nevertheless, further techno-economic analyses are required to provide statistically significant conclusions on profitability and feasibility. In particular, statements regarding the
economic feasibility of municipal food waste are based on a few nearly identical studies.

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Review: Economics of second-generation biorefineries

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