Reflection on the research on and implementation of biorefinery systems – a systematic literature review with a focus on feedstock

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Abstract: The concept of sustainably processing biomass into a spectrum of products and bioenergy is thousands of years old. Large-scale utilization of such processes existed in the 19th century and the term biorefinery first appeared in the late 20th century. This review addresses how different feedstock classes, products, and regions have been described in the scientific literature on the development of biorefineries (1999–2017). The results of a systematic literature review were compared with information included in two reports on the implementation of biorefineries to identify similarities and differences between theory (described in the literature) and practice (carried out in industry). The number of scientific articles per year on this topic has increased over the last decade, particularly in the fields of natural sciences and engineering. The first authors of these articles are primarily affiliated with North American and European institutions. References to lignocellulosic raw materials (especially residues, but also dedicated crops) in the feedstock are by far the most frequent and those to aquatic biomass have also increased over time. Most of the products mentioned are related to energy products (mainly fuels), and the heterogeneous class of chemicals was also strongly represented. We examined two reports on existing biorefineries in Europe and identified differences between the roles of food-crop-based biorefineries and lignocellulosic-feedstock biorefineries in terms of research and practice. New studies on the practical implementation of biorefineries should be carried out, with particular attention to these discrepancies. © 2019 The Authors. Biofuels, Bioproducts, and Biorefining published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Supporting information may be found in the online version of this article.

Keywords: biorefinery implementation; biorefinery research; bio-based products; bioenergy; bioeconomy; biorefinery feedstock
Introduction

Biorefineries will play an important role in the development of a bioeconomy. The term biorefinery can be considered somewhat analogous to petrochemical refineries. The International Energy Agency Bioenergy Task 42 defines this term as 'sustainable processing of biomass into a spectrum of marketable bio-based products (chemicals, materials) and bioenergy (fuels, power, and/or heat). The American National Renewable Energy Laboratory defines it as 'a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass.' In the 19th and 20th centuries, a push had already been made to utilize renewable resources on a large scale, and according to Bernntsson et al., the term biorefinery emerged later in the 1990s, when several industrial trends favored the use of biomass. According to the online dictionaries Merriam-Webster.com and OxfordDictionaries.com, the first known use of the term biorefinery dates back to the 1980s.

To cope with the increasing number and complexity of biorefineries, several approaches to classification have been introduced – for example, with regard to their technological implementation status, the types of raw materials that they use, the main types of intermediates, and the main conversion process types. Kamm and Kamm described four biorefinery systems that are frequently mentioned during research and development: lignocellulosic feedstock biorefineries, whole-crop biorefineries, and green biorefineries, as well as the two-platform concept and syngas. Van Ree and Annevelink distinguished between conventional biorefineries, green biorefineries, whole-crop biorefineries, lignocellulosic feedstock biorefineries, two-platform-concept biorefineries, thermochemical biorefineries, and marine biorefineries. Cherubini et al. developed a classification approach that is flexible and applicable to individual biorefinery systems and their possible combinations by distinguishing four main features. These are platforms (e.g., C5 and C6 sugars, oils, biogas), products (energy products such as electricity/heat and material products such as polymers), feedstock (dedicated crops, for instance, oil crops, grasses and residues such as lignocellulosic residues), and processes (e.g., thermochemical, biochemical, mechanical).

To promote the transition towards a knowledge-based bioeconomy, it is important to conduct research in various fields. Scientific progress has already led to a much better understanding of the underlying biorefinery processes and natural cycles. However, biorefinery development requires more than the provision of feasible technologies. The challenges that arise along the whole value chain need to be tackled and these involve many stakeholders and disciplines, including biomass cultivation, harvesting, logistics, processes (e.g., pretreatments, conversion, separation) and their optimization, life-cycle analysis, sustainability, and economic considerations.

The aim of this review was to reveal how different feedstock, products, and regions are reflected in the scientific literature on the development of biorefineries, taking into account the feedstock classes assigned by Cherubini et al. Furthermore, the results of the systematic literature review (approach based on Fink) were analyzed and compared with findings in reports on the current state of implementation of biorefineries to uncover similarities and differences between theory (described in the literature) and practice (carried out in industry). Such a review has not yet been made and this therefore offers new insights into the biorefineries and the feedstock used.

Compared to traditional petrochemical refineries, biorefineries have some different characteristics: various concepts are still under development; different feedstocks are used; and diverse and often immature processing technologies are employed. So there is, theoretically, a huge range of possibilities for linking feedstock with processes, platforms, and products.

We focused on the feedstocks in this review because they are the starting points for several conceivable paths, their availability is limited (there is a scarcity of cultivable land to meet the demand for food, feed, fuel, and materials), and because the production of biomass has a major impact on global issues, such as food security (e.g., the food-versus-fuel dilemma, competition for land), biodiversity, and carbon sequestration. In addition to considering feedstocks, we investigated the products / intermediates mentioned in these abstracts, the research aims (areas of research) addressed, and the geographical origins of the papers.

Few data are available for applied biorefineries; nevertheless, two reports on existing biorefineries in Europe were considered, and the trends and discrepancies in biorefinery research and practical implementation of biorefineries are discussed. The findings of this review will allow further insights to be made and discussions to be carried out in the broader context of a sustainable, knowledge-based bioeconomy.

Method and materials

Based on the classification approach established by Cherubini et al., a systematic literature review (approach based on Fink) was carried out to identify the feedstock
categories considered in the scientific literature. As Scopus® is multidisciplinary, and the world’s largest abstract database of peer-reviewed scientific literature, it has been selected for the review to ensure an appropriate overview.

The abstracts of 892 scientific articles (published between 1999 and 2017), which included the search terms biorefinery and feedstock in their titles, abstracts and / or as keywords were analyzed. Similar search terms (raw material, biorefining, biorefin*, and input material) were investigated as well; however, the two-word combination of biorefinery and feedstock was the most commonly used (led to the most hits). The search string TITLE-ABS-KEY (biorefinery AND feedstock) AND DOCTYPE (ar) AND PUBYEAR < 2018 was used to search for articles. No starting year was chosen, in an attempt to include even the earliest search results.

All abstracts were read, and the feedstocks that were mentioned were noted and assigned to the following classes (generally based on the Cherubini classification): (1) starch and sugar crops, (2) oil crops, (3) dedicated lignocellulose crops, (4) fresh ‘vet’ biomass (green biorefineries), (5) aquatic biomass, (6) other dedicated biomass (e.g., yeast), (7) lignocellulosic residues, (8) oleaginous residues, (9) lignocellulose (source not mentioned / either dedicated or residue), and (10) not specified (e.g., the term biomass). The respective feedstocks were classified according to Cherubini et al. and with the help of sources freely accessible via the Internet (such as the definition and classification of commodities by the FAO). The biorefinery products / intermediates, if mentioned in the 892 abstracts, were also considered and assigned to the following classes: (1a) energy products, (1b) fuel products, if the use was clearly indicated as fuel, (2) ethanol, and (3) gaseous compounds, if not explicitly mentioned as fuel, were noted separately because they might be used either for energy or chemicals, (4) chemicals including intermediates, (5) materials, (6) food and feed applications, (7) other applications that were not clearly assignable or too rare to form a separate class, and (8) unspecified uses (e.g., the terms biorefinery or value added products).

The abstracts that were identified were assigned to three categories according to the research objective mentioned:

1. Research aims in the fields of chemistry, technology, or natural sciences, such as conducting a compound analysis and investigating process engineering issues to answer respective research questions.
2. Primarily (techno-)economic or environmental (and to a lesser extent also social-scientific) research goals, such as lifecycle assessments and solving cost / price / logistics issues.
3. General approaches taken by authors that involve a more holistic / broader system perspective, as presented in review papers and articles that describe both technical and economic aspects.

The affiliation of the first author (country/continent) was taken into consideration and time trends (if available) were also analyzed.

Few data were available on the actual implementation of biorefineries, so two sources that deal with this topic (surveys conducted as part of the FP6 projects Biorefinery Euroview and Biopol, and by the nova-institute on behalf of the Biobased Industries Consortium) were examined to elucidate the discussion regarding research on and implementation of biorefineries. In the following section, the overall approaches taken to create these two reports are briefly described:

1. The researchers of the FP6 projects Biorefinery Euroview (current situation and potential of the biorefinery concept in the EU: Strategic framework and guidelines for its development) and BIOPOL (assessment of BIOrefinery concepts and the implications for agricultural forestry POLicy), funded by the European Commission, have published a joint deliverable that provides an overview of the state of the art of biorefineries in Europe. To obtain this overview, 2800 industrial stakeholders (from 16 EU countries plus Norway, Switzerland, and the USA) from different activity sectors were contacted and asked to complete a survey (consisting of a joint questionnaire). They received 110 responses (from 11 countries), which were further analyzed. Only facilities that produced two or more products plus energy (including fuel) were considered as biorefineries in this report. A total of 34 existing or planned biorefineries located mainly in Western Europe were identified (following the definitions of a biorefinery provided by Kamm and Soetaert and specified in the report, at p. 12). These included: cereal / whole-crop biorefineries, oilseed biorefineries, green biorefineries, lignocellulosic feedstock-/forest-based and lignocellulosic biorefineries, and multiple feed / integrated biorefineries. The list of 34 identified biorefineries (Appendix D – Identification of biorefinery sites in the European Union in File S1) was used as the basis for comparison during the review: The feedstocks listed in this table were assigned to the feedstock classes in the same way as in the systematic literature review.
2. On behalf of the BioBased Industries Consortium (BIC), the nova-Institute created a map of the European...
biorefineries, as no map was previously available that showed the locations of commercial biorefineries in Europe, and to visualize bio-based activities.\textsuperscript{18} By means of an online survey, respondents were asked to provide information about any ‘integrated production plant using biomass or biomass-derived feedstock to produce a range of value added products and energy’.\textsuperscript{22} A map and list of 224 biorefineries in Europe was published by the end of 2017 (yearly updates were planned), which were assigned to the following categories: sugar- / starch-based biorefineries for bioethanol and other chemicals; oil- / fat-based biorefineries either for producing biodiesel (first- and second-generation) or for oleochemistry; wood-based biorefineries for producing a range of products (e.g., pulp, bio-based chemicals, biofuels, electricity and heat; but omitting pulp for paper production only); lignocellulose-based biorefineries other than wood with a range of products (e.g., pulp / fibers, proteins, bio-based chemicals, biofuels, electricity, heat), and biowaste-based biorefineries with a range of products (depending on the underlying waste).\textsuperscript{18} As the publicly available list did not include the exact feedstocks, and, therefore, no assignment was possible as in the previous example, the feedstocks from the review were assigned based on the map’s classification to compare them with the results of the systematic literature review. Specifically, sugar and starch crops, oil crops and oleaginous residues, dedicated lignocellulosic feedstock, and the waste class were taken into account.

The results of the systematic literature review are discussed in more detail in the context of the findings of the application studies, highlighting differences between practical biorefinery implementation and the biorefinery research.

Results: biorefineries in the scientific literature

Figure 1 illustrates the increase in the numbers of scientific articles on the topic of biorefinery feedstock published per year using the underlying search string.

The abstracts considered were assigned to three categories according to the research objective stated. Figure 2 shows the occurrence of the categories over time. Abstracts that placed a focus on the natural sciences and technology were the most abundant and their numbers increased most rapidly over time.

In Fig. 3, the abundance of feedstock classes with regard to the research aims is illustrated. Abstracts that were assigned to the fields of chemistry, technology, or the natural sciences included information on the use of aquatic biomass, waste and, to a lesser extent, lignocellulosic residues as feedstocks more frequently than abstracts that mainly described (techno-) economic or environmental (and to some degree, social) research objectives. In contrast, this category represented sugar and starch crops, biomass that was not further specified, and, to a lesser extent, oil crops more strongly than the first category (chemistry, technology, natural sciences). Abstracts assigned to the third category (general approach, system perspective, review) included feedstock assigned to the class ‘biomass’ (feedstock that was not further specified) more frequently than abstracts that were assigned to the first two categories.

In Fig. 4, the affiliations of the first authors were taken into consideration. The country affiliations were assigned to regions (based on the UN geoscheme) and continents. This action was also performed for the co-authors’ affiliations, which led to similar results. Most articles (39\%) were published by authors affiliated with North American institutions, with affiliations in the USA representing 34\% of all abstracts considered, followed by authors affiliated with Canadian institutions (3\%). Authors affiliated with European institutions represented the second-largest group, with 22 countries represented (32\% of all abstracts): northern European institutions were at the top of the list, with the UK in first place (5\% of all abstracts), followed by Denmark, the Netherlands, and Sweden (3\% each). Abstracts from institutions in Asia accounted for 19\%, with China (5\%), Malaysia (3\%), and India (3\%) leading the list. Articles from authors affiliated with South American (6\%, mostly Brazil: 4\%), African, or Australian and New Zealand institutions were less common.

Despite the dominance of institutions in North America (Fig. 4), the number of articles published by authors based in Europe and Asia increased strongly over time (Fig. 5).

Figure 6 illustrates how frequently different feedstocks were mentioned with regard to the first author’s affiliation by continent. Abstracts published by first authors affiliated with institutions in North America placed a strong focus on lignocellulosic feedstock, and especially on dedicated crops. When sugar and starch crops were mentioned, they often referred to corn for ethanol production. Abstracts written by first authors affiliated with European institutions considered a rather wide range of feedstocks, with lignocellulosic materials (residues and dedicated crops) dominating. Compared with other continents, abstracts written by first authors affiliated with Asian institutions focused more strongly on marine biomass (algae). Abstracts of articles written by first authors affiliated with South
Review: Biorefinery research and implementation – a systematic literature review

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Figure 1. Number of scientific articles with the terms ‘biorefinery’ and ‘feedstock’ in their abstracts, titles, and/or as keywords (1999–2017; database: Scopus; n = 892 abstracts).

Figure 2. Research focus of articles on biorefinery feedstock (1999–2017; database: Scopus; n = 892 abstracts).

Figure 3. Abundance of feedstock classes with regard to the research aims (1999–2017; database: Scopus; n = 892 abstracts).
American institutions mentioned sugar, starch, and oil crops (especially sugarcane and oil palm) more frequently than abstracts of first authors affiliated with institutions on other continents. The majority of lignocellulosic residues, which represented the most common class, consisted of sugarcane residues (e.g., bagasse). The number of samples of article abstracts from authors affiliated with African institutions was very small, and the feedstocks described were non-food crops (mainly waste and residues; the one oil crop mentioned was non-edible).

Feedstocks – considerations and trends over time

Eight hundred and ninety-two article abstracts (1999–2017) were read and more than 150 terms for different feedstocks were identified, which were assigned to 11 classes. The results, including 1072 categorized feedstocks, are illustrated in Fig. 7. Feedstocks such as starch and sugar crops and oil crops appeared to be underrepresented (Fig. 8 shows that the number of these does not seem to...
Figure 6. Relationship between affiliation of first author by continent and topic of biorefinery feedstock mentioned in article abstracts (1999–2017; database: Scopus; n = 1045 feedstocks).

Figure 7. Relative frequencies of biorefinery feedstock mentioned in article abstracts (1999–2017; database: Scopus; n = 1072 feedstocks).
have increased significantly over time) but lignocellulosic feedstocks predominated, followed by aquatic biomass.

**Dedicated crops**

Lignocellulosic crops had the highest share of the dedicated feedstock group: 24% of all mentioned feedstocks were assigned to this class, and the number of abstracts increased comparatively sharply over the years considered in the study (Fig. 8). In this group, wood was the most common feedstock (especially poplar, pine, eucalyptus, and willow), closely followed by energy grasses such as switchgrass and miscanthus.

Aquatic biomass accounted for 10% of the total feedstocks mentioned, and a positive trend was noted since its appearance in 2008 in the literature considered here. When more specific algae were mentioned in the abstracts, microalgae (mentioned in approximately half of the abstracts in this class) accounted for most of them, whereas macroalgae were mentioned in roughly one-third of the abstracts on aquatic biomass. After lignocellulosic crops, this group of dedicated feedstocks showed the largest increase compared to other dedicated crops (Fig. 8).

The share of starch, sugar, and oil crops mentioned in the context of biorefineries was rather low. About 6% of the feedstock mentioned referred to starch and sugar crops and 3% to oil crops. Specifically, two-thirds of the abstracts that were assigned to the sugar and starch class mentioned corn or sugarcane as raw materials, while oil palm was the leading feedstock identified in the oil crop category. Wet ‘fresh’ biomass for green biorefineries had a rather small share (2%). This special feedstock for biorefineries appeared in 2006 in one abstract and again in 2010. Its use seems to have stabilized at a low level since then. The typical feedstock was mixed grass, whereas the only plant species mentioned several times was the perennial legume alfalfa.

**Residues**

Lignocellulosic residues were the most frequently mentioned feedstock class (27%). This group contained the greatest variety of feedstock sources, as residual material from various crops consists of lignocellulose: corn residues (stover, stalk, straw, cob) were mentioned in approximately one-third of the abstracts in this class, followed by wheat residues (straw, bran), forest and wood residues such as bark and branches, sugarcane residues (bagasse, straw), and residues of oil palm.

Around 7% of all the feedstocks mentioned were related to industrial or municipal waste (excluding lignocellulosic and oil-based compounds), which is generally very heterogeneous. The majority of abstracts in this class (around two-thirds) contained feedstocks that could be assigned to industrial wastes, including various components (for instance, byproducts from food processing industries and dried distillers’ grains with solubles (DDGS)), and municipal wastes such as food, clothes, paper, and mixed waste. In addition to the classes of dedicated and residual lignocellulose biomass and aquatic biomass, references to industrial and municipal waste showed a positive trend over time (Fig. 9).
The class of oleaginous residues (including glycerol from plant oil production) accounted for only 1% of all feedstock mentioned. These residues were mainly related to glycerol, waste oil, and cooking oil.

**Platforms and products**

The abstracts that mentioned biorefinery feedstocks were screened for references to intended products or intermediates. These were subsequently assigned to nine product classes. One thousand three hundred and seventy-eight products / intermediates were identified among the 892 abstracts (Fig. 10).

Energy products (excluding fuel) accounted for 8% of all the stated and assigned products. In the abstracts that mentioned a more accurate term than simply energy, the term electricity was most common, followed by power and heat. Among the fuels, which accounted for almost 24% of all the feedstocks mentioned, diesel was the most common term, followed by ethanol, which was explicitly mentioned as being used for fuel applications. Substitutes for gasoline and butanol were also mentioned, but only in a few abstracts.

Gas and ethanol were presented in separate classes if a specific purpose (such as fuel) was not mentioned, as they could be used for the purposes of both energy and chemical production. Gaseous compounds accounted for 4% of all the products mentioned with most references being made to hydrogen, followed by syngas and methane.

The group of chemicals (25% of the products mentioned) contained a greater variety of specific compounds, including various acids (mainly succinic acid and lactic acid, followed by acetic and levulinic acid), furfural, polyhydroxalkanoates (polyhydroxybutyrate), and diols (butanediol, propanediol, and ethylene glycol), but also antioxidants, xylitol, and enzymes.

Material applications comprised a rather small group: 6% of the products considered referred to assignable materials, such as polymer and fiber applications (e.g., pulp and paper, composites, biobased plastics).

Food and feed applications accounted for 3% of the products (around two-thirds of feed and one-third of food and food additives).

The category other (3% of products mentioned), which comprised small and not clearly assignable product groups, contained, for instance, pyrolysis oil, fertilizer, and biochar. The category not specified mainly contained general expressions such as biorefinery or value-added products and accounted for 12% of all the products mentioned. Figure 11 illustrates the development of the products mentioned in scientific abstracts on the topic of biorefinery feedstock over time and demonstrates (see Fig. 10) the predominance of energy applications. However, the proportion of chemicals was observed to increase slightly over time, and the diversity of different applications discussed in the literature grew.

Figure 12 illustrates the relative frequency of the products mentioned with regard to the first author's affiliation by continent. The general pattern seen was quite similar but some variations could be observed. Between the articles published by authors affiliated with institutions in North America and Europe, the most common class differed: the first authors affiliated with North American institutions placed
the strongest focus on fuel applications, while first authors affiliated with European institutions tended to take chemicals more strongly into account. Authors with affiliations in South America often described ethanol production and mainly from sugarcane. The sample of first authors with African affiliations was small; however, a stronger focus seems to have been placed on food, feed, and fertilizers.

A product mentioned in an abstract was investigated in connection with the feedstock in this abstract – the resulting combinations of products and feedstocks that were mentioned in the respective abstracts are illustrated in Table 1, whereby some typical patterns could be observed.

Lignocellulosic feedstocks were typically mentioned in abstracts along with chemicals and fuels as the intended products. Aquatic biomass was generally understood as oil-producing algae that were used to substitute for, e.g., kerosene and other oil-based fuels (e.g., diesel). Ethanol and (other) carbohydrate-based fuels (e.g., gasoline substitutes) were produced from lignocellulosic biomass but also from edible starch and sugar crops. Materials tended to be mentioned in the context of dedicated lignocellulosic feedstock, and abstracts that mentioned the production of gaseous compounds often referred to lignocellulosic residues (e.g., microbial gasification).
Results: scientific research versus actual implementation

Available data on existing biorefineries in Europe\(^{18,19}\) indicated the proportions of the feedstocks in the classes proposed by Cherubini et al.\(^9\) that were different from those identified in the examined scientific abstracts.

Figure 13 illustrates 45 feedstocks derived from 34 practical examples extracted from the joint report of the FP6 projects Biorefinery Euroview and BIOPOL\(^9\) (as described in the methods section). Dedicated starch, sugar, and oil crops were mainly used, and they accounted for 44% of all feedstock described. Lignocellulosic residues represented 18% and fresh biomass from green biorefineries 16%, followed by lignocellulosic crops (9%), lignocellulosic biomass of unknown origin (5%) and oil-based residues as well as aquatic biomass (each category 2%).

Compared to the results of the systematic literature review (taking into account the abstracts with first-author affiliations in Europe), the FP6 report was dominated by starch and sugar crops as well as oil crops (FP6 report 44%; scientific abstracts 7%). Wet ‘fresh’ biomass for green biorefineries was also more frequently mentioned in this report (FP6 report 16%; scientific abstracts 4%). Biomass of lignocellulosic origin (FP6 report 32%; scientific abstracts 56%) and, in particular, the sub-class of dedicated lignocellulosic crops (FP6 report: 9% scientific abstracts 22%) dominated the systematic literature review. Aquatic biomass (FP6 report 2%; scientific abstracts 10%) occurred more frequently in the abstracts as well.

In Fig. 14, the feedstock classes assigned by the nova-Institute\(^8\) (on the basis of 224 selected biorefineries) are compared with the corresponding feedstock classes identified in the literature review (dedicated lignocellulose crops, domestic and industrial wastes, sugar and starch crops, oil-based feedstocks).

In the report on the existing European biorefineries compiled by the nova-Institute, oil-based biorefineries accounted for the largest share of the biorefineries that were considered. Two classes were defined for oil / fat-based biorefineries (first- and second-generation biodiesel amounted to 29% and oleochemistry amounted to 24% of all biorefineries considered). Sugar / starch-based biorefineries for the production of ethanol and other chemicals made up 28%. In comparison, only 9% of the feedstocks mentioned in the scientific abstracts examined (with first-author affiliations in Europe) referred either to oil crops or oleaginous residues, and only 11% referred to sugar- and starch-based feedstocks.
In the nova-Institute report, lignocellulosic feedstocks accounted for 13% (11% wood; biorefineries producing pulp for paper only were excluded; 2% used lignocellulosic feedstocks other than wood), and the 13 biorefineries that were considered and used biowaste made up a share of 6%. In the scientific abstracts, these two groups were more pronounced: 62% of the feedstocks referred to dedicated lignocellulosic crops (wood or other), and waste feedstocks made up a share of 18% of those mentioned in the abstracts examined.

Discussion

Limitations

Although the database was selected and the search string chosen to the best of the authors' ability, and Scopus claims to be the largest database of peer-reviewed literature available, not every relevant article might have been captured. The words *feedstock* and *biorefinery* needed to appear in the abstract, keywords, and / or title; as *biorefinery* is a relatively new term that describes an activity that has existed for a long time, it is unlikely that everything that would fit the definition of a biorefinery would be called this by the author. The limited number of articles that had been published prior to 2006 might also have been due to the lack of awareness of the term. It is therefore important to consider that the abstracts found with the help of the underlying search string reflect their authors' perceptions that their articles were on the subject of biorefineries, rather than they reflect the *biorefinery research* by definition. The term *feedstock* also does not necessarily have to be mentioned in the considered abstracts – for example, the feedstock might simply be mentioned by name (e.g., wood). However, the large number of articles that have been considered for this study reduces the likelihood of relevant systematic biases when considering the general patterns that have been observed.

Although we evaluated the occurrence of the term *feedstock* quantitatively, these results do not provide any information about the expected usage volume of these materials. This must be considered in the interpretation of the results, especially in the context of the practical implementation of biorefineries.

We analyzed the affiliation of the first authors of these articles to make a regional statement. However, if the publication was written by several authors who were affiliated with institutions in different regions of the world, it was not possible to identify the origin of the article's conceptualization. In the scientific community, researchers frequently change their locations (e.g., due to mobility programs or funding opportunities), and we found that an article written by a first author from an

Table 1. Products from feedstock classes in scientific articles on biorefinery feedstocks (1999–2017; database: Scopus; n = 1690

| Energy (incl. Heat, electricity, power) | Sugar and starch crops | Oil crops | Lignocellulose crops | Other dedicated crops (e.g., aquatic biomass, lignocellulosic residues) | Other dedicated crops (e.g., hydrolysates) | Oleaginous residues | Industrial and domestic waste | Not specified (e.g., bioactive compounds) | Biorefinery (not further specified) | (column totals) |
|---|---|---|---|---|---|---|---|---|---|---|
| Sugar and starch crops | 12 | 31 | 3 | 3 | 0 | 2 | 6 | 0 | 1 | 108 |
| Oil crops | 28 | 3 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 4 |
| Lignocellulose crops | 35 | 60 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 27 |
| Other dedicated crops (e.g., aquatic biomass) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Oleaginous residues | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Industrial and domestic waste | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Not specified (e.g., bioactive compounds) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Biorefinery (not further specified) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| (column totals) | 108 | 27 | 2 | 2 | 0 | 0 | 0 | 1 | 0 | 10 |

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institution in one region might be concerned with a biorefinery and an underlying feedstock in another part of the world. We considered a large number of articles in this study and observed a general pattern. We assume that this general pattern would remain even if underlying biases were removed.

The geographic scope of the studies, which focused on biorefinery sites, was limited to Europe (nova-institute, BIC) and the EU countries plus Norway, Switzerland, and the USA (FP6 report), whereas the literature review took into account literature (in English) that was geographically unlimited. Neither the lists of implemented biorefineries nor the results of the literature review can be regarded as complete, and both the methods applied and the classification method differed from each other. Another limitation concerns the comparison with the biorefinery map. As no feedstocks were contained in the published list, we assume that the counting and assignment of the feedstocks was not performed in the same way as the procedure undertaken in the scientific literature review. Under these circumstances, we do not recommend that
readers compare the exact numbers. Instead, we encourage readers to consider these numbers in a broader context to gain a bigger picture of general trends and divergences in biorefinery development in research and practice.

The assignments to different classes (feedstock, products, research aims) were to some extent subjective but we increased intersubjectivity by discussing the approach and the results with other researchers.

**Overview of scientific articles on biorefinery feedstocks**

The fact that the numbers of scientific articles on the topic of biorefinery feedstock published per year have increased over time, as illustrated in Fig. 1, confirms the findings of a study in which a scientometric approach was taken to biorefineries. The author of this study stated that the research output on biorefineries in general has grown exponentially over the preceding decade.24 The results of the systematic literature review indicate that this trend has continued since that study was published in 2012. Nevertheless, it should be borne in mind that, overall, more articles are being published in more peer-reviewed journals now than in the past (with differences between research areas), as stated by Larsen et al.25

Articles that focused on the natural sciences and technology were the most widely represented in our dataset, and their numbers increased more over time compared to those in other research areas. In particular, more research has recently been conducted on non-established biorefinery types such as algae biorefineries and on the valorization of lignocellulosic residues as well as various domestic and industrial wastes (Fig. 2). Kamm and Kamm²⁶ stated that the biological and chemical sciences would play important roles in the development of future industries. To ensure the development of economically profitable and sustainable biorefineries, several challenges must be tackled along the whole value chain: new approaches in industry, research, and development must be taken, which also involve a range of different scientific disciplines.⁶,¹³

**Biorefinery feedstocks and products described in the scientific literature – considerations and trends over time**

Bio-economy strategies and policies that could bring possible comparative advantages most likely explain why specific feedstock and products are being considered in different regions of the world. These strategies and policies, which involve different rationales, focal points, and priority areas for government interventions, have been launched in different regions and countries around the world.¹⁰,²⁶ For instance, Orts et al.²⁷ described the first wave of commercially available biorefineries in the USA (corn-starch ethanol plants) as being the result of the Renewable Fuel Standard of 2007 (which is an expansion of the Renewable Fuel Standard established in 2005) and its incentive programs. The installation of second-generation biorefineries to produce goods from non-food feedstock²⁸ (e.g., from lignocellulose) is making progress – however, commercialization has still had limited success.²⁷

The results of the literature review indicate that biofuels still drive biorefinery research. The energy-/fuel-driven biorefineries usually produce value-added products (often on a small scale and with high value) because the production of fuels and other energy products (often on a large scale and with low value) alone might not allow the biorefinery to operate profitably.²⁹ Other biorefineries (for instance, those in the pulp and paper industry) produce various valuable products, and their residuals are typically used for the purpose of energy production. Simultaneously integrating the production of chemicals and fuels could have a positive impact on the objectives of substituting fossil resources and building a robust biorefining industry.³⁰

To produce fuel, the so-called first-generation biorefineries use edible crops as feedstocks using conventional technologies, and mature commercial markets exist for this fuel.¹⁵,¹³,³² Several concerns arose, however, that were related to competition for resources necessary for food production.³¹,³³,³⁴ The second-generation biorefineries use non-edible feedstocks such as dedicated lignocelluloses, lignocellulosic residues and wastes,³⁵ which are not in direct competition with food and feed crops. However, if not managed sustainably, there is a risk of negative, indirect effects.³¹

Many efforts and much progress have been made to increase the value of lignocellulose, but commercialization has in many cases not yet been successful, for instance because of the so-called recalcitrance of lignocellulose.²⁸,³⁴–³⁶ Algae biorefineries (sometimes referred to as third-generation biorefineries) offer several possibilities and have the advantage of not competing for arable land,³¹ but there are still some challenges to overcome on the path towards commercialization.³¹,³⁷ Consequently, basic scientific issues regarding the respective feedstocks used in the so-called advanced biorefineries and uncertainties (e.g., concerning technologies and possible applications) lead, on the one hand, to extensive research being needed to achieve the necessary technological advances and feasible, optimized production systems and, on the other hand, to difficulties in terms of practical implementation at present.³¹,³⁸ The strong increase in the number of articles on biorefineries and lignocellulosic algae and residue-based feedstocks
indicates that increasing importance is being assigned to the development of second- and third-generation biorefineries. With regard to the search terms used in this study, our results indicate that authors working in these fields tend to perceive their work as biorefinery research.

A future economy that uses bio-based resources sustainably to meet people's needs will depend on the production of a variety of products such as food, feed, materials, chemicals, and energy from limited resources (e.g., land, energy, water, nutrients). These will need to be used as efficiently as possible. In the long term, a systemic perspective should therefore be maintained to fulfill all these needs simultaneously, taking into account regional and global factors, instead of emphasizing a single product category.

Several technologies are available in the field of renewable energy to produce sustainable energy (e.g., solar energy, wind energy, hydropower, geothermal energy). They do not necessarily depend on making use of the energy value of biomass. In contrast, the majority of organic chemicals and polymers depend on fossil-based resources: Approximately 9% of the fossil-based gases, oils, and coal used are produced for non-energy applications, which account for about 16% of oil products if the energy required for production is included. Bozell stated that 25–30% of the annual profits from integrated petrochemical refineries can be attributed to the small amount of crude oil dedicated to the production of chemicals. Chemicals have a higher value on a unit basis compared to fuels. Bio-based chemicals usually play a role when special functions need to be provided. These chemicals are usually sold on the high-value but low-volume specialty and fine chemicals market, as the low price of crude oil hampers commodity production. Nevertheless, several drivers (e.g., volatile oil prices and insecure supply, consumer demand for more environmentally friendly products) and other favorable circumstances could lead to the production of bulk chemicals in the future.

In this regard, for example, the US Department of Energy issued reports on promising building blocks for chemicals in 2004 (sugars and synthesis gas, which were revisited in 2010, and lignin). From a technical point of view, almost all fossil-based industrial materials could be replaced by bio-based equivalents; however, these often cannot compete economically and perform at least as well as their petrochemical counterparts, and are more sustainable at the same time.

Materials accounted for a small share of the products identified in the literature review; however, many substances included in the highly diverse class of chemicals can be precursors for the production of materials (for instance, bioplastics from PHB). These two classes, therefore, cannot easily be distinguished from each other. Furthermore, some traditional industries produce materials (e.g., paper, board) and value-adding co-products and are by definition biorefineries, but may not define themselves as such.

**Scientific research versus actual implementation**

When comparing reports that describe the practical implementation of biorefineries with the results of the systematic analysis of abstracts, we observed a significant difference regarding the consideration of different feedstocks. This could be due to the data-collection procedure used to gather the practical examples. We assumed that there was a systematic bias introduced during the data collection because almost every modern pulp mill could by definition be considered a biorefinery. The world's highest volumes of traditional non-food biobased polymers are produced with paper and board and the pulp and paper industry is considered one of the key industries for the integration of biorefineries. These mills are product-driven biorefineries (which usually produce energy as a co-product) and they have existed for a long time. These facts might prevent them from being perceived as biorefineries.

Our analysis did not allow us to identify a precise starting point that might have led to the current situation regarding industrial biorefineries. For example, biofuel policies had already been put in place in response to oil price hikes in the 1970s (creation of biofuel ethanol markets in the USA using corn, and in Brazil, using sugarcane), so a demand, a market, and an industry for biofuels were already present when the relatively recent promotion of biofuels occurred. In the European Union, where many vehicles are equipped with diesel engines, oil crops have played a major role in policies to replace part of the diesel fuel. The fact that national and regional strategies and policies, conventional technologies to process sugar, starch, and oil crops and markets already exist in this area could be reasons for the strong representation of these feedstock in the reports on the implemented biorefineries. Apart from that, waste-based and aquatic biorefineries (and, to a certain degree, lignocellulosic-feedstock biorefineries) might be strongly represented in the scientific abstracts because, generally, the technologies used are not as advanced and commercialization has not yet taken place.

**Conclusions**

Our results suggest that lignocelluloses and, in particular, lignocellulosic residues are the dominant biorefinery feedstocks in the published research. Lignocellulosic
feedstocks cover a comparably broad product portfolio, are easily available, and do not compete strongly with food and feed. Furthermore, fuels and other energy-related products still dominate the overall product portfolio of biorefineries in research and development, but other products are being considered with increasing frequency. If this trend continues, biorefinery product portfolios may become increasingly diversified, which is a prerequisite for the broader implementation of the biorefinery concept.

The observed increase in the amount of research dedicated to biorefineries based on lignocellulose and algae, as well as concepts utilizing residues rather than first-generation feedstocks, could be a result of the food-versus-fuel debate. Biorefineries based on aquatic biomass are also in earlier stages of development, and those based on lignocellulose are often still struggling to overcome technical barriers (e.g., the so-called recalcitrance of lignocellulose) – they are therefore also strongly represented in the scientific literature.

We identified significant differences between the roles of food-crop-based biorefineries and lignocellulosic-feedstock biorefineries in terms of research and practice. Although the potential reasons for this gap are still unclear, the potential roles of lignocellulosic biorefineries should be further investigated. New studies on the practical implementation of biorefineries should be conducted, paying additional attention to this gap. Reasons for the observed differences can most probably also be found in the existing agro-industrial and forest-industrial structures, which play especially important roles in the implementation of biorefineries. This aspect should therefore also be investigated in further research.

The development of biorefinery classification systems about 10 years ago clearly contributed to the structure of the discourse on biorefinery concept development.7–9 The study’s results indicate that the classification systems are relevant, especially when a broader perspective is taken of biorefineries. Consistent and comparable classification systems and a clear statement of what is considered a biorefinery are necessary to capture, evaluate, compare, and communicate appropriately the current status and developments in the field of biorefinery research and practice.

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