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Overview

The bioeconomy needs economic, ecological and social sustainability

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Abstract: The economic concept of the circular bioeconomy addresses not only the sectors of the traditional bioeconomy but also, in particular, the sectors of bio-based chemicals and energies as well as waste management. This concept is basically based on closing material cycles, in particular, but not only, that of carbon. Managing these material cycles is costly, which is why economic sustainability and, in the current transition phase, competitiveness with fossil-based value chains remain a constant challenge. Because of the large material turnover of the mentioned industries, in the interest of environmental sustainability the circular bioeconomy has to respect the limits of natural resources. With the raw material shift from fossil to renewable resources, regional economic structures and jobs will change and, in addition, circularity requires a change in consumption behavior. Both are challenges that need to be addressed in the interest of social acceptance and sustainability. The article focuses on the economic, but addresses also the ecological and social aspects, discusses options for achieving a comprehensively sustainable circular bioeconomy, and identifies research needs necessary for the further development of the bioeconomy.

Keywords: circular bioeconomy; economic sustainability; ecological sustainability; social sustainability; chemical industry

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1. Introduction

Common definitions of the bioeconomy focus primarily on biomass and producing materials and energy from it in order to achieve a more ecologically sustainable economy than the current one which is based on fossil raw materials [1]. The raw material changes from fossil to renewable carbon and energy sources, that is necessary in the interest of climate protection and due to the dwindling fossil resources, is unquestionably a decisive element of the bioeconomy, but to emphasize this alone leaves other important aspects unconsidered. The real difference to the current economic approach in linear value chains is the closing of material cycles, especially, but not only, that of carbon. This is why the term circular bioeconomy is increasingly used, which the World Economic Forum defines very comprehensively as "a conceptual framework for using renewable natural capital to transform and manage our land, food, health and industrial systems, with the goal of achieving sustainable wellbeing in harmony with nature [2]. Correctly, nature compatibility or, in other words, ecological sustainability is demanded, because the natural carbon cycle using nature's capital, on which the biomass production of agriculture and forestry is based, must not be overstrained.The article therefore analyzes the question of the raw material demand of the bioeconomy for industrial purposes, whether this demand can be met by primary biomass in a sustainable way and what possibilities there are to unburden production capacities by recycling residues and wastes. Such a circular economy requires comparatively complex and energy-intensive production and recycling systems. However, this makes it difficult to compete with fossil-based value chains, which still largely externalize the ecological damage costs they cause. To achieve economic sustainability, therefore, economic policy frameworks need to gradually offset this competitive distortion. The article examines whether the current framework accomplishes this task. Implementing the circular bioeconomy is not only a technical and an economic challenge, but also a social one. That rural areas will gain economic importance and employment with more intensive industrial use of biomass is generally accepted, but the article also raises the question of whether this can be accompanied by changes in existing industrial centers. In addition, consumer behavior must be adapted to the requirements of closed material cycles. To be comprehensively successful and socially accepted, the circular bioeconomy must therefore achieve economic, ecological and social sustainability in equal measure. The state of research allows many of these questions to be analyzed only qualitatively. In conclusion, economic, ecological and social fields of investigation are identified for further quantitative research.

2. Methods

Scientific publications that are accessible online as well as reports from authorities were evaluated. In order to be able to take into account the status of economic practice, publications from companies were also included. All sources of information are cited. The evaluation followed the principles of the Methodology published by Bergs et al. (2020) [3] on the ecological and economic assessment of manufacturing process sequences. The PESTLE methodology [4] was used to include political, economic, social, technological, legal and environmental aspects in the analysis.

For the online research, the following search words were used: bio-economy, circular bbioeconomy, biomass, residuals, waste, agriculture, forestry, chemical industry, energy sector, bio-energies, bio-fuel, waste management, processing, greenhouse gas, carbon dioxide, emission, employment, food, feed, bioenergy, bio-based chemicals, bio-based materials, sustainability, economic, ecological, societal, social, regulations, European Commission, emissions trading system, Europe, world.

3. Results

The rising concentration of greenhouse gases in the atmosphere is increasingly changing the climate [5]. Greenhouse gas emissions from manufacturing industries, the energy sector, mobility, and the operation of buildings, still running on fossil raw materials, but also anthropogenic emissions of non-fossil origin, such as parts of agricultural emissions are the essential cause [6]. Changing this by reducing greenhouse gas emissions and achieving a balance of emissions and sinks for climate protection is one of the most important drivers for the circular bioeconomy [7]. Climate protection addresses an important aspect of environmental sustainability. In addition, the bioeconomy must also achieve economic sustainability and, last but not least, it can only gain social acceptance if it is designed to be socially sustainable.

The traditional bioeconomy is driven by the biomass-producing sectors of agriculture and forestry, the biomass-processing sectors of food and feed, the wood industry, and the sectors of the cellulose, paper and fiber industries. Increasingly to be integrated are the chemical sector and the energy industry (heat, fuels, electricity), and to close material cycles, the participation of the waste industry is indispensable. A detailed overview of the affected sectors according to NACE is given by Kardung et al. [8]. In the following, particular attention will be paid to the new industries to be integrated.

3.1. Economic Sustainability

The economic sustainability is determined, among other things, by the economic costs of the raw materials, the processes, the energies, the plants and the duration of the return on investment, the labor costs and, last but not least, the economic policy framework conditions [9]. As long as fossil raw materials are on the market, the competitive situation with them must also be illuminated. De Jong et al. [10] have presented a comprehensive overview of this for biobased chemicals in 2020.

3.1.1. Raw materials

The pure cost of biomass production suffers from a cost disadvantage compared to fossil feedstocks [11–14]. Unlike fossil feedstocks, which are highly concentrated at regionally limited deposit sites mainly in Russia, the Middle East, West Africa, North and South America, and Australia biomass is cultivated in a land-intensive manner and with correspondingly complex logistics [15–18]. With the involvement of numerous suppliers such as the seed industry and chemicals (pesticides, fertilizers), the value chain to biomass is complex [19]. In addition, the harvested biomass consists, unlike fossil raw materials, from very different chemical components like lignocellulose, sugars, starch, proteins, fats and oils, and more or less water. While water is relatively low in cereals, it accounts for an average of 75% in sugar beets and up to 89% in potatoes, for example [20]. Therefore the carbon density of biomass is only 47–51% on average, in contrast to fossil raw materials (oil, coal, gas) with a carbon content of 75–95% [21,22]. Depending on the target product, only some of the biomass components can be processed, some remain on the field as residual materials, and some is residue from processing, such as chaff or corn husks from starch plants or press cake from oil plants such as rapeseed and soybeans. Today, these residues are used in a low-value way as stable fodder (straw) or animal feed (oil press cake) [23]. The water contained in the biomass cannot be utilized at all or at most as a substrate for biogas fermentation [24]. The analysis of the distribution of chemical elements shows that biomass contains a lot of oxygen compared to fossil raw materials. As examples, Table 1 shows the composition and heat value of fossil and biogenic raw materials and product groups of fossil-based basic chemicals (olefins, armoatics) and products of biorefineries (sugar and lignocellulose) (Table 1) [25].

Table 1. Composition of fossil and biogenic raw materials.

	Carbon	Hydrogen	Oxygen	Moisture	Heat value
	Percent dry mass			Percent fresh weight	MJ/kg dm
Natural gas	75–85	9–24	Traces	Traces	32–45
Mineral oil	83–87	10–14	0,5–6	Traces	43
Black coal	60–75	6	17–34	25–33	
Olefins	84–86	14–16			
Aromatics	91–92	8–9			
Vegetable biomass	45	6	42	<89	6,8
Wood	50	6	41	6–14	14,4–15,8
Starch	44	6	50		17,5
Lignocellulose	44	6	50		10–25

On the one hand, it becomes clear that the product groups of the basic chemistry (olefins, aromatics) have a similar composition to the fossil raw materials (natural gas, mineral oil) from which they are produced. On the other hand, with the lower carbon and the higher oxygen content there are significant differences with biogenic carbon sources such as starch and lignocellulose. This composition represents a significant cost burden for processing into chemical products. Biomass can also be used as an energy source, but it has a much lower heat value compared to fossil feedstocks, which inevitably increases the cost of bioenergies.

As will be discussed under environmental aspects, primary biomass from agriculture and forestry will have limited availability for industrial purposes. Therefore, previously neglected biowastes such as municipal shrub and grass clippings, wastewater treatment residues (sewage sludge), and biomass processing residues such as carbon dioxide are increasingly being investigated [26]. In addition to producing compost, shrub can be used for heat and power generation in the same way as wood in combined heat and power plants and grass cuttings can be valorized in biogas fermentation [27]. Sewage sludge can be applied directly as fertilizer to cropland at low cost [28]. Alternatively, sewage sludge can be fermented via biogas fermentation to produce bio-methane, which can serve as a heat source, a fuel, and a carbon source for chemical processes [29,30]. While the inclusion of these materials in the bioeconomy's feedstock portfolio relieves pressure on primary biomass production capacity, it also leads to costly process steps. For example, biogas (bio-methane) production costs $9-16/MBtu today and is expected to remain in the range of $3–17/MBtu (excluding feedstock) over the long term [31,32]. In contrast, natural gas (methane) costs between 0.24 USD/MBtu (Iran) and 1.2 USD/MBtu (UK) to produce [33,34].

Carbon dioxide, residue from numerous biomass processing operations, can also serve as a sustainable carbon source for fuels (e-fuels) and chemicals [35,36]. However, the upgrading of carbon dioxide (CCU; Carbon Capture and Utilization) requires hydrogen, the production of which is energy-intensive and thus expensive [37–39].

3.1.2. Processing

The composition of the biomass has a direct influence on the cost structure of the processing operations. For example, the refining of biomass leads to a variety of residues in addition to the desired target products, for each of which a further use must be found if possible [40–42].

A common residue from the processing of biomass fractions such as sugar is carbon dioxide, which is emitted by the microorganisms of biotechnological processes. Plants for the production of bioethanol and amino acids, to name just two examples, emit considerable volumes of carbon dioxide, and biogas contains an average of 40% carbon dioxide [43–45]. Because the carbon of the emission comes from the biogenic feedstock, the emission significantly reduces the substrate yield of biotechnological processes and in this way is also cost effective. For example, the theoretical maximum yield of glucose-based ethanol fermentation is 51% [46,47].

3.1.3. Energies

Biomass can also serve as a source of energy. 74% of the bioenergy consumed in Europe is bio-heat and 13% each is bio-fuels and bio-electricity [48]. Overall, bio-energies contribute 60% of renewable energy (EU 2019) [49]. Biomass is also used for the production of the gaseous energy carrier bio-methane (biogas) and biofuels such as biodiesel and bioethanol. Today, bio-methane is directly consumed as a heat source or converted into electricity [50,51]. Biodiesel, for example is produced from rapeseed oil, and bio-ethanol from sugar and starch [52,53]. Bioenergies are successful on the market because the economic policy framework conditions promote this [54]. Their role will be addressed below.

3.1.4. Production equipment

Over the entire value chain from biomass production to the end product, the capital expenditure for equipment is high because, as already mentioned above, numerous processing steps are involved [55–57]. Another difference between bio- and fossil-based processes is the suitability for low-cost continuous processes. While this is the state of the art for fossil-based processes, biotechnological processes generally run in batches, which reduces plant efficiency due to the necessary preparation times [58]. On the other hand, biotechnological processes succeed in running multi-stage biosynthesis chains of the production organisms in a single fermenter. Fossil-based syntheses, on the other hand, would require a separate unit for each of the individual synthesis steps. The economic sustainability of the individual process steps compared to fossil-based plants therefore depends strongly on which process step is considered. However, another major difference between fossil-based and bio-based plants must be mentioned. The largest oil refinery in the world has a capacity to process 62 Mt of crude oil per year with a carbon content of about 54 Mt [59]. As an example of large-scale biorefineries, reference should be made to bioethanol plants. The largest European bioethanol plant has a capacity of 400,000 m^3 ethanol (315,000 tons) containing 164,000 tons of carbon [60]. Although this comparison is highly simplified, it makes clear that the capacity of bio-based plants is much smaller than that of oil refineries. This considerably limits an important factor for economic efficiency, the economy of scale [61]. The reason lies in the complex logistics of biogenic raw materials, which limits the catchment area of a biorefinery and thus also the capacity.

3.1.5. Labor costs

The statements made for the cost of equipment also apply in principle to the cost of labor. Due to the large number of steps from raw material production to the end product, and the lower capacities, the labor costs over the entire process chain are comparatively high. In contrast, individual production steps such as the fermentation mentioned above can be less labor-intensive compared with fossil-based plants.

3.1.6. Framework conditions

The previous remarks have shown that primary biomass, biogenic residues and waste have fundamental cost disadvantages compared to fossil raw materials because of the way they are produced and their composition. This also applies in principle to processing and production facilities [62]. This is being addressed in Europe through various mechanisms at the national and international levels. At national level, for example, renewable energies (including bio-energies) are promoted (Renewable Energies Act (EEG) in Germany) [63]. The taxation of greenhouse gas emissions, especially from fossil sources, is intended to make them more expensive and to push them back. In Europe, 18 countries price GHG emissions ranging from EUR 0.07 (Poland) to EUR 166.33 (Sweden) per ton of carbon dioxide-equivalent [64]. At the EU level, the Emissions Trading Scheme (EU ETS) makes fossil fuel emissions more expensive, especially those from power generation (SCOPE 1, 2). This instrument is further strengthened by reducing the number of allowances each year [65]. For fuels such as bioethanol, advanced bio-ethanol and biodiesel, the EU prescribes minimum quotas and, in order to mitigate the food versus fuel conflict, also maximum quotas [66,67].

3.1.7. Market development

The effectiveness of the framework policy measures is reflected in the development of the affected industries. The industries covered by the EU emissions trading system (energy-intensive industries of energy, steel, aluminum, glass, chemicals, etc.) have in fact significantly reduced their emissions, even though production volumes have increased [68]. For example, the chemical industry has reduced its emissions by 59%, while increasing production by 78% (1990–2016) [69]. Bio-fuels have a market that meets the prescribed quotas [70]. Therefore, while bio-based fuels compete with each other, they are excluded from competition with fossil-based fuels by the quota system. The pricing of carbon dioxide emissions through the EU ETS has led to a reduction in emissions in the sectors covered, preferably where energy-related SCOPE 1 and 2 emissions have been reduced [71]. SCOPE 3 emissions, which are caused by the use and disposal of products, are not covered by the EU ETS. In the chemical sector, for example, this is leading companies to accelerate their transition to zero-emission energy, but continue to use fossil carbon sources for the carbon contained in products, which can be released as SCOPE3 emissions. For example, bio-based chemical products have only reached a 4% production share in the EU [72]. However, it should be noted that the EU ETS covers only 60%

of the EU's domestic emissions; 40%, including the significant emissions from agriculture, are not priced so far [73].

3.2. Ecological sustainability

There is a consensus in society, business, science and politics that the current fossil-based economy is ecologically unsustainable. This is primarily due to the enormously large consumption of oil, natural gas and coal in linear value chains. These production chains begin with the extraction of fossil raw materials, continue with their processing into products, and end with the emission of most of the carbon they contain into the atmosphere in the form of carbon dioxide. This applies in particular to energy generation by combustion, which accounts for over 90% of the fossil raw materials consumed worldwide. Material conversion into asphalt and products of organic chemistry, on the other hand, binds the carbon, at least as long as the products are in use. An overview of the global flows of fossil feedstock to chemicals is given by Levi and Cullen [74]. However, when the products are disposed off after use, e.g. by waste incineration, the carbon they contain is also released as carbon dioxide.

Sustainable carbon management therefore requires above all that carbon in the form of carbon dioxide is not accumulated in the atmosphere, but that the carbon cycle is closed in circular value chains [75]. In the bioeconomy, this is done by the natural carbon cycle of photosynthesis with the sun as the energy source. In this cycle, the carbon of biomass feedstocks is processed into products and emitted into the atmosphere as carbon dioxide when the products after use are disposed off by incineration or biological degradation, but is fully sequestered again by photosynthetic fixation into new biomass. Thus, the accumulation of carbon dioxide in the atmosphere can theoretically be completely avoided [76].

In this way, the concept of the bioeconomy represents a sustainable alternative to the fossil-based economy. However, to replace it completely, it would also have to be able to provide the volume of carbon consumed with fossil resources. Fossil feedstocks with an energy content of 136,761 terawatt-hours were consumed in 2019 for energy production only [77]. This is equivalent to 11.8 bn toe (tons oil-equivalent) with an estimated carbon content of about 9.9 bn tons. However, the global agricultural and forestry sectors produce only 9.2 bn tons of crop biomass (2019) and 5.7 bn tons of wood biomass (2019) containing together about 7.45 bn tons of carbon annually [78,79]. Thus, to fully replace fossil carbon, agriculture and agribusiness would have to produce more than twice that amount of carbon. Because biomass contains on average 50% carbon, the production of biomass would have to be increased by a factor of 3.5. However, this theoretical claim is opposed by sustainability limits such as the planetary boundaries and ecosystem services, which have already been damaged in some cases. The planetary boundaries of the phosphorus and nitrogen balance and the integrity of the biosphere are classified as evidently disturbed [80]. The ecosystem services essential for biomass production are also already restricted, at least regionally [81]. Replacing fossil raw materials completely with biomass is therefore not a realistic option.

The question must therefore be asked which of the industries that have so far processed fossil raw materials are dependent on carbon and which are not. The largest consumer of fossil raw materials worldwide is the energy sector with over 90%; in 2017, this sector accounted for 93% in the USA [82].

Converting this sector even partially to bioenergies would result in large land requirements for biomass production and therefore risk increasing deforestation unless economic policy guardrails are put in place [83]. With solar and wind energy, hydropower, geothermal energy and nuclear energy, carbon-free energies are available for electricity generation. Heating and cooling can basically be generated with electricity and thus carbon-free. The same applies to mobility, which increasingly relies on electric drives. Only parts of heavy-duty transportation, especially air travel, may remain dependent on high-energy-density carbon fuels for the foreseeable future. British Airways, for example, will be the first airline in the world to use sustainable aviation fuel (SAF) based on biogenic residues in routine operations from 2022. [84]. So, at least largely converting the energy sector to carbon-free energy is possible and can reduce the demand for carbon for bioenergies.

The situation is different for the chemical industry. Organic chemistry, by definition, requires carbon. This industry must be integrated into the bioeconomy and supplied with non-fossil carbon sources. Worldwide, the chemical industry today binds around 450 Mt of carbon in its products [85]. However, in biotechnological manufacturing processes, a carbon loss of up to 50% must be accepted, so that the carbon demand can increase to up to 675 million t. With a carbon content of around 50%, this volume of carbon translates into 1,350 Mt of biomass, which would correspond to more than 12% of global production. However, such an increase has to be seen against the background of the increasing demand for food, the already ecologically overloaded agricultural areas and the limited ecosystems services. In the interest of sustainability, therefore, there is a call to set land aside rather than to expand. In addition, the ecological footprint that an expansion of land or an intensification of agriculture would entail must be taken into account. After all, today 24% of global emissions are due to agriculture [86].

For this reason, alternatives to primary biomass are increasingly being sought and developed. As already mentioned, they can be found in biogenic residual and waste materials, including carbon dioxide [87–89]. The use of these residual and waste materials as raw materials represents a closed carbon cycle, but without the intermediate step of emitting carbon dioxide into the atmosphere, as occurs in the natural carbon cycle. Instead, the carbon remains in a technical cycle, with zero-emission energy required as the energy source. It is thus foreseeable that technical carbon recycling will become more important for industrial applications of the bioeconomy, which is why the term circular bioeconomy has been introduced. With the importance of these technical cycles, it becomes clear at the same time that the achievement of sustainability of a circular bioeconomy will depend quite significantly on the achievement of a sustainable energy sector to fuel hydrogen production for CO_2-recycling [90].

3.3. Social sustainability

The implications that go hand in hand with economic and environmental sustainability make it clear that the upcoming transformation of the economy is not a raw material change alone, nor just a technical process, but will change employment in the affected industries. The low-cost logistics of fossil raw materials (natural gas and crude oil in pipelines and large tankers; coal in bulk carriers and rail), their easy storability over long periods of time, and their year-round availability have led to the emergence of very large-capacity industrial centers. They are supplied with raw materials by extremely efficient global supply chains. These locations are partly close to the regions of raw material production (for example Jubail; Saudi Arabia) or in distant industrial countries (for example the cross-border chemical region ARRR (Antwerp, Rotterdam, Rhine, Ruhr) in Belgium, Germany, The Netherlands).

Biomass processing chains need a different infrastructure. Biomass is produced on large areas and its logistics and storage are costly. At least the early processing stages of these raw materials will therefore tend to take place in the raw material regions. Bringing intermediate products to the specialized industrial centers for further processing is an option, but the commodity regions may develop an interest in retaining later stages of value creation as well. For example, in Brazil, the developed infrastructure for ethanol production based on sugarcane may become the starting base of a chemical sector originating from ethanol [91]. It is therefore plausible to expect that jobs will be created in rural areas and possibly even that jobs will shift from traditional industrial centers to rural areas [92]. Because, as shown above, the employment intensity of biomass production and comparatively small-scale biomass processing is higher than in the fossil-based economy, higher production costs must be expected [93,94]. On the other hand, funds are saved for ecological damage that would be caused by the processing of fossil raw materials. Because these have so far been largely externalized, the higher costs of bioeconomy products can be perceived by consumers as a loss of purchasing power. This, in turn, can weaken social acceptance of the bioeconomy as a whole and negatively influence purchasing decisions for bio-based products. Although Morone et al. (2021) [95] report that in Italy, for example, the willingness to pay a "green premium" for certified bio-based products is generally increasing, consumers differentiate between product groups. Preference is given to bio-based products in the food, nutrition and personal care categories. Because of the importance of certification to a purchasing decision, Majer et al. (2018) [96] examined the need to standardize certification and identified the necessary research needs.

4. Discussion

The bioeconomy is already a significant economic factor i) in its traditional industries of food, wood and derived sectors such as cellulose and paper and ii) in sub-sectors of bio-based chemistry and energies [97]. However, a complete conversion of chemicals and energies would not be sustainable due to a lack of sufficient biogenic feedstocks. Therefore, a prioritization on organic chemical products and only a part of the energy markets, which today still rely on carbon-based energies, is necessary. Even this focus poses a challenge for the production of primary biomass by agriculture and forestry, which must be done in a sustainable way, that is, respecting planetary boundaries and preserving biosystem services. From this follows the need for intensification of raw material efficiency through the use of products after use or waste through recycling. However, this evolution of the bioeconomy concept, originally focused on the use of primary biomass, into a circular bioeconomy entails increased energy requirements, especially when recycling carbon dioxide is included in the spectrum of carbon sources. Where the economically and ecologically optimal ratio of primary biomass production and recycling lies, when all-consuming sectors and energy demand are considered, is still unexplored. However, it is an important area of research so that companies can make forward-looking decisions and governments can formulate the framework conditions with target-oriented control instruments.

Altogether, the bioeconomy faces cost disadvantages as long the environmental damage of the fossil-based economy is largely externalized in business terms, as it has been in the past. This is the reason why bio-based chemicals have so far failed to gain economic acceptance in applications where they compete on cost with fossil-based products. In order to achieve the raw material shift towards a circular bioeconomy, externalized ecological damages must become effective as business cost factors. A quantitative analysis of this factor is a relevant research need, the results of which could be used in the formulation of framework conditions, e.g., emission fees.

Not only in order to improve the competitiveness of the bioeconomy compared to the fossil-based economy, but also to avoid undesirable developments of the bioeconomy to the detriment of sustainability, control instruments that place an economic burden on ecologically damaging modes of operation must be further developed. In this context, an ecological damage potential is not limited to the fossil economy, but is also inherent to the bioeconomy. Planetary boundaries must be respected and ecosystem services, on which the bioeconomy is particularly dependent, must not be overburdened. A price tag must be placed on potential degradation, and the effectiveness of the control instruments used for this purpose must be analyzed.

In the bioeconomy, the demand for biomass will increase the importance of rural areas and create jobs there for the production, harvesting and storage of biomass and its processing in biorefineries. This can be assumed for industrialized countries as well as for emerging global regions with high biomass potential. There is also the potential to establish early and, as development progresses, higher stages of value-added processing and thus create employment. The extent to which jobs can be shifted from industrial centers to rural areas and from industrialized countries to global agricultural regions depends, among other things, on which regions can create the necessary infrastructure and supportive framework conditions early on and acquire investment funds. The scientific analysis of these possible dynamic economic and social changes must differentiate according to value creation stages and the length of value chains. Short value chains from raw material to product, as is the case e.g. for fuels, are produced more possibly in the raw material region, as is the case today for bio-ethanol. Similar can be assumed for products of bio-based basic chemistry, which are produced in a biomass region or in the case of recycling e.g. close to a carbon dioxide source. In contrast, for higher value-added stages that produce functionalized products such as active pharmaceutical ingredients in highly specialized plants, it can rather be assumed that centralized plants offer the appropriate infrastructure. Here, too, there is still a need for differentiated research.

Social sustainability not only requires the creation of jobs by industry, but also requires a change in consumption behavior. Consumption must be able to be integrated into sustainable circular value chains by making any residual materials and waste that are produced recyclable. However, recyclability will only be credibly incorporated by consumers into their purchasing behavior if recycled products become part of the product range on a large scale. Today, however, the general conditions with the preference for energy recovery from municipal waste stand in the way of this. This possible connection between consumer behavior and the framework conditions postulated here, which should actually only represent a control instrument for the industry, would be an interesting object of investigation.

These complex economic, ecological and social developments of global scope are taking place against the background that fossil raw materials can still be produced comparatively cheaply compared to those processed in the bioeconomy. Producers of oil, gas and coal can therefore take advantage of margins of price reduction that producers and processors of biomass do not have because of the comparatively higher fixed costs. In order to make the transition to a circular bioeconomy economically sustainable, efficient governance and framework conditions adapted to the requirements of the bioeconomy are therefore needed [98–100]. The framework for this is provided by the UN Sustainability Goals (SDGs), because the circular bioeconomy can contribute to 12–14 economic, ecological and social goals of the total of 17 SDGs [101–103]. Achieving this triad of economic, environmental and social sustainability is the key success factor for the circular bioeconomy. Time is of the essence here, because in order to limit global warming to 1.5 ℃, the consumption of fossil raw materials must be reduced by 3% annually by 2050 while the circular bioeconomy must be developed in parallel [104].

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Conflict of interest

The author declares no conflict of interest.

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