Perspective

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More sustainable biomass production and biorefining to boost the bioeconomy

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Abstract: The ongoing saga of the fossil carbon-based economy affects the wellbeing of this planet and its associated life forms, including humans. Although the bioeconomy is widely advocated as a solution, it is not growing quickly enough due to various challenges. Here, we discuss emerging opportunities to overcome these barriers and enhance the bioeconomy's potential to contribute to achieving the United Nations' Sustainable Development Goals as a result of developments in biomass production and biorefining. A brief overview of current advances in biomass production, biorefining, and products together with their applications is provided. A comprehensive vision for the development of a sustainable bioeconomy is also given. Leveraging scientific and technological advances along with the support of modeling, assessment, and analyses, can help to address the sustainability concerns of the bioeconomy and accelerate its progress toward a carbon-neutral future while strengthening bioeconomy concepts of contributing to equitable economic growth based on holistic sustainable development in harmony with nature. © 2021 Society of Industrial Chemistry and John Wiley & Sons Ltd.

Key words: biomass production methods; biorefining processes; sustainable bioeconomy; sustainable development goals; rural development; climate change

Introduction

The world is reeling from environmental, biodiversity, and societal crises arising from anthropogenic activities.[1] The United Nations has outlined 17 Sustainable Development Goals (SDGs) for a secure and sustainable future.[1] To achieve them there must be an economic paradigm shift.[2] The development of the bioeconomy is crucial to this transition.[3–5]

The biobased economy or bioeconomy represents an inclusive and sustainable economic system comprising sectors of industry and trade involving various streams of biomass production and biorefining to provide services, processes, and products while protecting the environment and biodiversity. Here, biomass production refers to making renewable plant matter that can be utilized commercially. Biorefining is the sustainable transformation of biomass into bioproducts (food, feed, chemicals, and materials) and bioenergy (biofuels, electricity, and heat).[6,7] Biomass production and biorefining are separate but interrelated sectors, both of which are crucial to the success of a sustainable bioeconomy.

The bioeconomy played significant roles in ancient civilizations by providing most products. As a result of fossil

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carbon-based industrialization utilizing coal, petroleum, and natural gas, bioeconomy applications became confined mainly to food and feed. As sustainability concerns are increasing, the bioeconomy, with a wide range of possibilities, is once again gaining the attention of the public, industry, the scientific community, and other stakeholders. However, its progress is slow for several reasons, including misconceptions, insufficient scientific communication, public awareness, and stakeholder engagement. To stimulate interest in various bioeconomy sectors, it is important to strengthen the discussion of opportunities from advances in biomass production and biorefining and their contributions to achieving global sustainability.

This article discusses (i) the bioeconomy's potential for addressing major global crises; (ii) emerging opportunities from advances in biomass production and biorefining for the development of the bioeconomy while deliberating on challenges; and (iii) a comprehensive vision to accelerate the growth of sustainable bioeconomy.

Scope of the bioeconomy in mitigating major global crises

Globally, several environmental, ecological, economic, societal, and psychological crises persist (Fig. 1), most of which are interrelated in many ways.[8] For decades, the bioeconomy has been advocated as a solution to mitigate such crises and to achieve several SDGs (Fig. 2).[4,5]

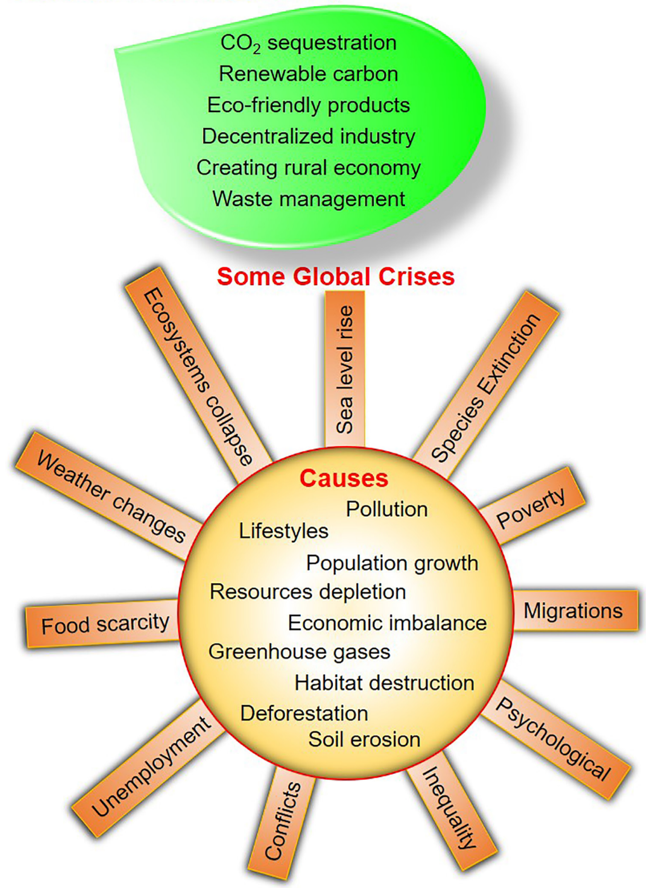

Figure 1. Current global crises and causes, and solutions from the bioeconomy.

Environmental and ecological damage

A healthy environment is vital for life on our planet. Globally, fossil carbon-based industrialization has grown rapidly without due consideration of its environmental impact. The extraction, manufacture, consumption, and disposal sectors involved in its economy pollute air, soil, and water, causing harm to humans and other species.[1,9,10] Earth has been dominated by humans for the last 12 000 years (Holocene era), but ecosystems remained relatively stable until the last two centuries. With modern industrialization and human population growth, the world is facing the sixth great mass extinction of species (Anthropocene era).[11] A recent IPBES-global assessment report mentions that about one million species are facing extinction.[12] An estimated 60% of coral reefs will be damaged by 2030 and the oceans will contain more plastic than fish by 2050.

The adaptation to the bioeconomy offers three significant environmental benefits: (i) halting the conversion of fossil carbon sources into CO_2; (ii) fixation of excess CO_2 as biomass and bio-based products; and (iii) preventing pollution from fossil carbon-based products and processes by providing environment-friendly alternatives. Crucially, these products can be reused, recycled, consumed, or converted into other products in a circular economy model, thereby minimizing disposal and pollution issues. With development and restoration of natural ecosystems, the bioeconomy promises to transform the fate of this Anthropocene era from fatal to constructive.

Economic, societal, and psychological crises

The fossil carbon-based economy is unevenly distributed within and among nations because the fossil carbon sources, which are being exhausted, are available in a few locations, limiting the industry to bulk processing in a centralized manner, confined to a few regions.[13] This contributes to an imbalance in GDP per capita between rural and urban areas, income inequality, a decline in rural employment, migration, economic crisis, and an increase in unemployment due to large industrial machineries and their automation.[14] As the

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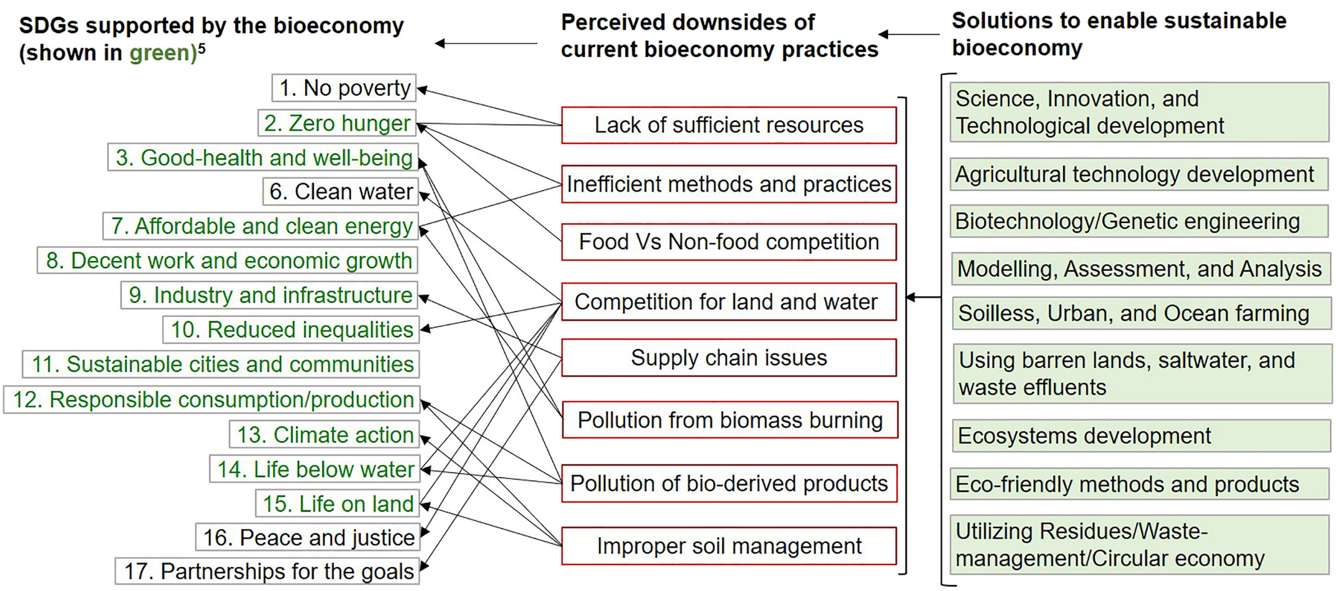

Figure 2. Solutions for sustainable bioeconomy development to contribute to achieving SDGs.

poor are generally most vulnerable to climate change, human development is at risk and conflicts occur more often due to scarcity of sources and resources, climate change, and economic crises, which are often interrelated.[14] Rapid growth in demand for goods and an expanding population may increase this risk.

Growing problems and awareness of the situation are causing psychological and societal problems. The public is trapped in polluting lifestyles with plentiful supplies and tends be incautious about this situation.[2] The only option is therefore to innovate and provide better products.

In ancient civilizations, the bioeconomy was the greatest source of employment and GDP. Now, its restoration is considered necessary to mitigate climate, economic, and societal crises. The bioeconomy can meet the challenges set by the UN to realize the green-economy.[15] As biomass production is largely rooted in rural areas, it can benefit rural economies and farmers by providing them with greater employment.[16,17] The bioeconomy can enable the public to enjoy guilt-free consumption by providing affordable non-polluting products for all.

As several global crises are interrelated,[8] the bioeconomy's positive impacts can be compounded and far-reaching.[4,5]

Current debate, barriers, and challenges in developing the bioeconomy

Although the bioeconomy is considered to mitigate several global sustainability crises, it has certain challenges, barriers, and controversies (Figs 2 and 3).[5,18–20] In Kircher's opinion, the transition to the bioeconomy is much more challenging than the transition from a pre-modern bioeconomy to the current fossil carbon-based economy.[21]

Current biomass production practices, which rely on resources whose availability is limited and soil management that is poor, are inefficient and insufficient for projected future food consumption. They increase risks of poverty, exploitation, and desertification.[5,22–24] Expanding such practices for commercial non-food products further increases risk due to food versus non-food competition and the perceived direct land-use change and indirect land-use change (ILUC).[25]

The currently used biomass has an undesirable structure and composition, low growth rate, and low mass density and energy density. These are less suitable for energy and many other commercial applications and create supply chain issues for the biorefineries. Continuous production and supply of biomass is necessary to sustain the biorefineries.[26]

The net efficiency of converting through biomass sunlight to heat / electricity is lower due to low sunlight-capture capacity, pollution during burning, less utilization of released heat, and tedious processing of wood-biomass for liquid and gaseous fuels.[27]

The use of drop-in strategy methods for converting biomass to chemicals and plastics that are similar to fossil carbon-derived ones would not benefit the environment as they cause similar pollution. Some chemical methods are introduced for direct sequestering of atmospheric CO_2 as chemical precursors.[28]

Moreover, it is challenging to replace the existing fossil carbon-based industry due to the fact that it is well

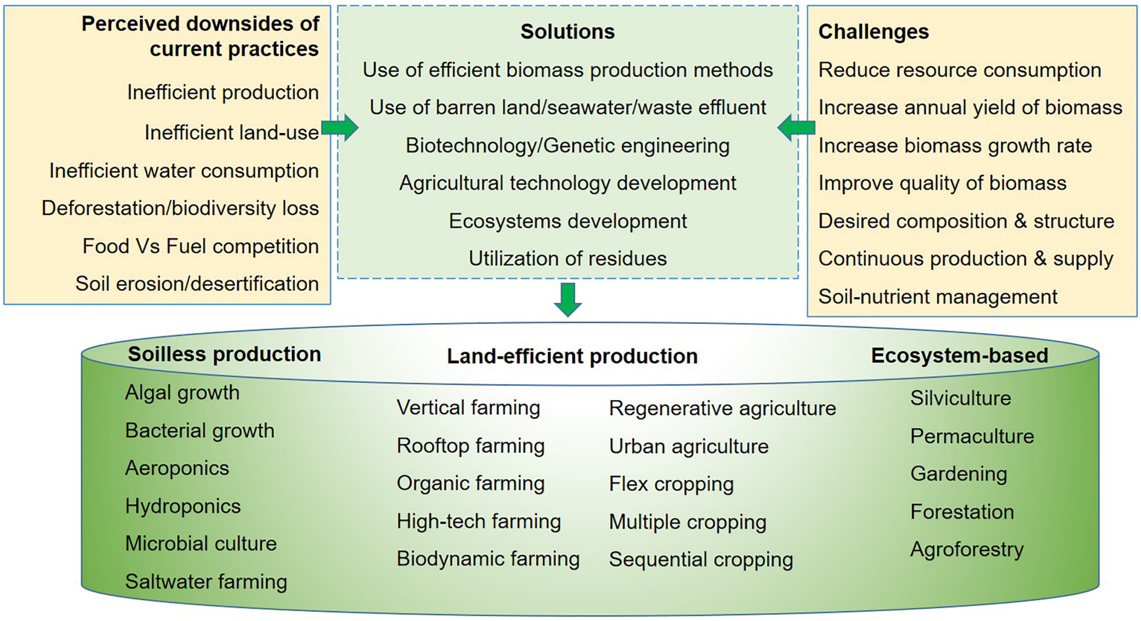

Figure 3. Solutions to concerns and challenges in biomass production.

established and the economies of entire nations depend on it.[14,20] Many nations have already imposed restrictions on food exports due to scarcity, and the export of other bio-based products is likely to become more difficult.

Opportunities, progress, and solutions for sustainable development of the bioeconomy

The bioeconomy differs in many ways from the fossil carbon-based industry and other primary sectors, and it has many advantages.[7,13,29] In particular, it has advantages over the fossil carbon-based economy, as summarized in Table 1. The bioeconomy can help towards the creation of a sustainable world economy.

The increasing processing cost, effort, and energy input for fossil carbon sources in contrast with the decreasing costs and technological developments in biomass production and biorefining indicate favorable conditions for the development of the bioeconomy.[21,30] Other renewables such as solar and wind may not be able to meet all needs, and electrification is unlikely to be viable in many sectors such as marine, aviation, and heavy transport and machinery.[30,31] The heating, electricity, and transportation sectors need biofuel participation as an alternative or supplement. Considerable municipal and agro-residual biomass is available for energy, and efficient biomass energy utilization systems are being developed.[30,32]

There are clear benefits from adopting bio-based alternatives to non-fuel fossil carbon-derived products, due to their environmental friendliness, low quantity requirements, and the lack of other renewable resources. Existing chemical strategies for conversion of CO_2 to chemicals are not as diverse, effective, economical, or environmentally friendly as biomass production and biorefining.

Technical, resource, and sustainability concerns in developing the bioeconomy can be addressed in an interdisciplinary manner by advanced biomass production and biorefining models with scientific, technological, and socio-economic innovations and analyses (Fig. 2). To support this, the current advances and opportunities in various sectors of bioeconomy is discussed in the following sections.

Science, innovation, and technology

Science, innovation, and technology are reshaping lifestyles with surprising inventions and products. They can now facilitate rational approaches to biomass production and biorefining for selecting methods and precursors, developing products, and optimizing processes. They can also help in formulating policies for regulating the various sectors that constitute the bioeconomy.[33] The potential for engineering the biological systems and integrating the principles of green chemistry and green engineering to create sustainable value chains is being realized.[34,35] Systems thinking and interdisciplinary approaches are evolving continuously toward the achievement of sustainability.[36] These can now all provide

Table 1. Advantages of the bioeconomy compared with the fossil carbon-based economy.

Subject	Fossil carbon-based economy	Bioeconomy
Source type	Non-renewable fossil carbon sources	Renewable biomass resources
Source locations	Contained in a few regions of few nations	Can be produced in a variety of places worldwide
Industrial scale, locations, and activity	Concentrated as large-scale operations and confined in a few zones for the reasons given above	Can be small scale to large scale in rural and urban areas for the reason given above
Logistics and supply-chain	Operate over long distances for the reasons given above	Can be flexible and operate over short or long distances for the reasons given above
Industry and business	Functions with centralized authority for the reasons above	Can function in a decentralized manner by local authorities for the reasons given above
Employment involved in industry	Uses highly mechanized industry with less employment for the reasons given above	More people with a range of skill levels to be employed for the reasons given above
Economic equality inside and among regions	Difficult to achieve for the reasons given above	Relatively more opportunities to achieve for the reasons given above
Polymers	To be obtained by polymerization of chemicals	Biopolymers can be used directly or post-treatment
Processing toward chemicals	Requires chemical processes and mostly involves oxygen addition	Bioprocesses can be used and mostly involve oxygen removal from major components such as cellulose
Pollution and eco-compatibility of processes and products	Most reagents, solvents, process effluents, and products are toxic pollutants	Can provide non-polluting, non-toxic, edible, and biodegradable products using non-polluting aqueous-based processes

opportunities for the development of the bioeconomy to fulfill the demands of society while addressing environmental, ecological, and economic challenges. There is much progress in scientific and innovative approaches for various stages, resulting in different methods for biomass production, biorefining, and product applications, as discussed below.

Biomass production

For different regions with environmental and resource limitations, many suitable biomass production methods are available or are being developed to avoid potential drawbacks such as deforestation, soil-degradation, biodiversity loss, or water and food scarcity (Fig. 3). These can improve biomass production for food and other products, and address biomass quality, quantity, and supply-chain issues.

Methods of minimized land and resource use include: vertical farming;[37] high-tech farming to minimize the use of water, energy, soil, time, etc.; organic and biodynamic farming to improve soil quality and produce biomass year round;[38] rooftop farming[39] and urban agriculture[40] for urbanized areas and houses; and sequential (one after another), multiple (many at the same time), and flex (one for many applications) cropping methods to provide food, bioenergy, and other services with minimal use of land and resources.[41,42]

Methods of soilless culture systems[43] include: hydroponics to produce biomass in nutrient water media where wastewater effluents can be used;[44] microbial, algal, and bacterial culture to produce specialty products;[45] aeroponics to minimize water and nutrient use;[46] and ocean-based and other types of salt-water farming to reduce dependence on freshwater.[47]

Integrated farming methods through ecosystem-based design include permaculture, silviculture, agroecology, and agroforestry. These approaches contribute to ecosystem restoration, reforestation, gardening, water conservation, sustainable land-use management, and self-sufficient biomass production for the benefit of biodiversity, the environment, and rural economies.[25,48,49] The use of barren lands through regenerative agriculture by improving soil-fertility with agro- and municipal wastes can complement demands for biomass and promote carbon sequestration.[32]

Biotechnology is progressing toward increasing biomass yield, changing biomass structural and chemical morphologies, increasing capture efficiency of CO_2 and light, developing plants to grow faster and larger with available resources and conditions, and enabling them to grow in barren lands.[29] Biotechnology is also working on the next phases such as storage, pre-treatment, and conversion. Agrotechnology is also being developed to increase biomass growth and yield through monitoring external conditions such as light, temperature, humidity, nutrients, water, and soil.

Biorefining

Biorefining facilitates value chain development by manufacturing various products from different components of a range of biomass sources with distinct properties,

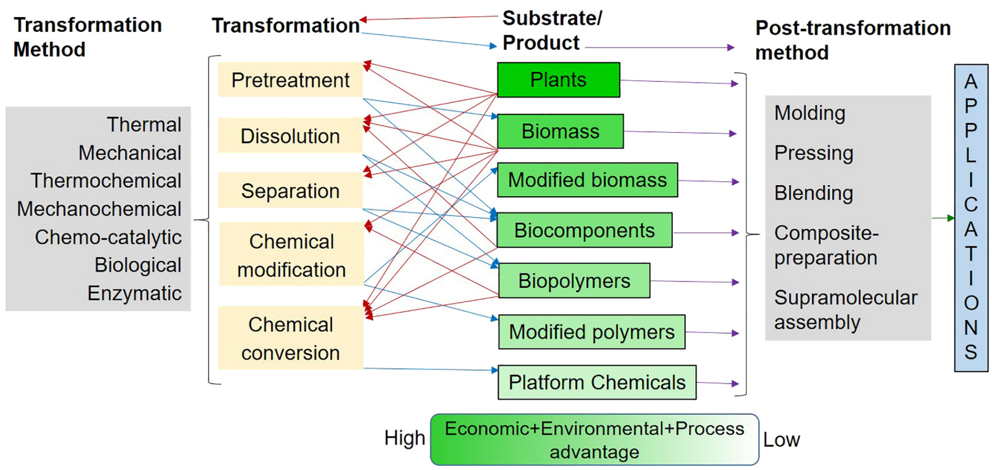

Figure 4. Stages, methods, and components of biorefining.

applications, market value, and other characteristics (Fig. 4).[50–52]

Biomass contains various components such as cellulose, hemicellulose, lignin, starch, fatty acids / glycerides, peptides, and terpenes.[50] Biomass can be treated to varying degrees, including as raw material, modified biomass, biopolymers, modified polymers, monomers, modified monomers, and chemicals.[29,53–56] Multiple transformation methods can be used – for example mechanical, mechanochemical, biochemical, chemical, thermochemical, or thermal.[7,29,30,56–58] From a technological perspective, various steps are being developed such as pre-treatment, dissolution, chemical modification, depolymerization, chemical conversion, and fractionation / separation.[59,60] From a chemistry perspective, several disciplines can be involved, such as catalysis, supramolecular assembly, separation, chemical conversion, chemical engineering, analysis, and characterization.[61] Biological and synthetic catalysts are being developed for more selective and efficient conversions.[62] For longer bioproduct shelf-life, modifications are underway to add bacterial, fungal, and termite resistance properties. To reduce the dependence on biomass production, models for utilizing agro-industrial and municipal organic wastes are being developed with the aim of achieving a sustainable circular bioeconomy.[29,63,64]

Overall, biorefining has the potential to provide replacements for all fossil carbon-derived products while minimizing cost and pollution, either through similar (using drop-in-strategies) or alternative (using emerging strategies) products. Products can be made either directly out of biomass and components of it (bio–/bio-based), or indirectly from their chemical transformations (bio-derived). By harnessing the opportunities from scientific and technological advances, simple processes comparable to those for making bread or wine can become commonplace.

Applications

Science and technology is progressing in identifying or innovating applications for biomass precursors and their derivatives, to obtain food, feed, biofuels, and many other products (Fig. 5).[29] Various biomass sources such as microalgae,[65] macroalgae (seaweed),[66] bacteria, and terrestrial plants can already be utilized for various products and applications, and novel uses will continue to be discovered based on functional properties.

Among a plethora of examples, live plants may be involved directly in the bioeconomy through gardening and reforestation as both a tourist attraction and a source of biomass. Algal and bacterial biomass can be used for nutritional supplements or alternatives to meat and dairy to avoid animal farming concerns and for more efficient food consumption. Large quantities of biomass can be utilized directly or following minimal treatment, in food, feed, heat / electricity generation, construction,[67,68] furniture, appliances, toys, and packaging.[69] Separated biomass components such as cellulose, hemicellulose, starch, peptides, and lignin can be used in various applications such as paper, furniture, and stabilizers.[70] Treated components, including nano-cellulose and microcrystalline cellulose, and dissolved polymers (plus their modified derivatives) can be used in composites, aerogels, clothing, plastics, etc.[71,72] Platform chemicals can be used in a range of applications from fuel-additives to pharmaceuticals and cosmetics. Bio-based product wastes can be used as nutrients for soil and organisms.

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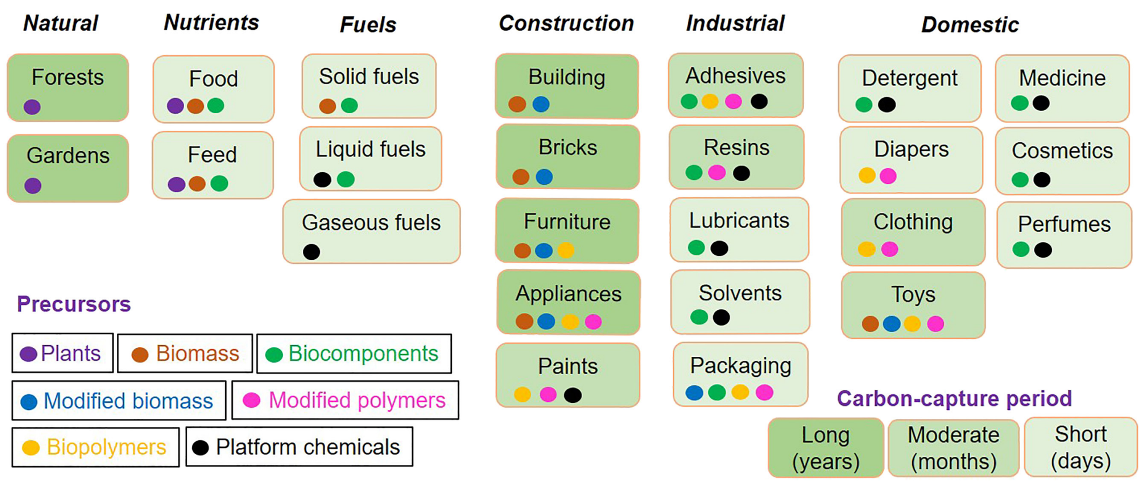

Figure 5. Application examples for bio-based precursors.

Applications can be created for a crop's main products together with residues and product wastes to increase biomass utilization and profits. Overall, most of society's needs from basic to specialized, and on a small to large scale, can be met, while also capturing and relocating atmospheric and oceanic carbon, either temporarily or over longer periods of time.

Modeling, assessment, and analysis

Successful design, development, and monitoring of any complex system like the bioeconomy, which is necessary for the achievement of SDGs, requires various types of modeling, assessment, and analysis to chart a roadmap from beginning to end.

Such methods are either available or in progress for various stages of the bioeconomy. These include: life-cycle, sustainability, techno-economic and economic assessments and analyses for biomass production, pretreatment, biorefining, product utilization, and waste management;[7,20,73–77] eco-compatibility and environmental and ecological footprint analysis for processes and products;[78] toxicological assessment of the impacts of products on the health of humans, plants, and other organisms;[10] and assessment of the impact of industrial waste on the environment, to develop mitigation strategies.[79] Many sophisticated tools facilitate detailed understanding of lifecycle mechanism of molecules in the environment.[80] Indirect land-use change is being understood to prevent its possible negative impacts.[25,30]

Together, these can support the bioeconomy at all stages: the selection of raw materials, products, and processes; drafting regulations, permits, and certification; conceptual design, optimization, and monitoring of biomass production and biorefining; estimating the cost, energy, and atom economy for an industry; mapping the order of priority of methods for sustainable biomass utilization; and adding the concepts of the green and circular economy to boost the bioeconomy. Collectively, these can make a significant contribution to overcoming the inherent challenges and achieving the SDGs.

Industrial, business, and rural development advantages related to the bioeconomy

Many supportive advantages are emerging for the growth of the sustainable bioeconomy: current industrial targets for products to achieve environmental friendliness, non-toxicity, biodegradability, and frugal productivity; mounting public interest in and rejection of existing polluting products alongside enthusiasm for novel products;[81] less competition from fossil carbon-based industrialization in regions where it has not yet been developed; and ongoing transitions into the sixth long wave of the economy and the fourth Industrial Revolution, which are in the initial stages and are anticipated to be driven by resource efficiency and clean technology.[82]

Distinct biomass production and biorefining characteristics position the bioeconomy to function especially well for rural development: the expansion of biomass production for commercial products; a preference for decentralized, small-scale industries and businesses due to the widely spread locations of biomass production and difficulties in transporting low-density biomass;[16,83] and better rural-compatibility because of biomass production when compared with fossil carbon-based sectors. As access to literacy, digital information, and technology increases, rural people can more readily find, learn, adapt, and practice new skills related to biomass production and biorefining. Large-scale urban industries tend to have a catalytic role in the growth of rural economies through utilizing and participating in innovation, commercializing outputs, and supplying equipment, chemicals, enzymes, etc.

Engaging in the bioeconomy has notable advantages for trade and business. If bioproducts are produced without negative impacts on human health, the environment, and biodiversity, then permits for their production, export, and marketing would be easier to obtain. This enables inter-regional trade and benefit the nations with sustainable economic growth and employment leading to friendlier international policies and relations.

Governmental and intergovernmental opportunities

Governments play a crucial role in formulating, initiating, and monitoring new policies, and they function as networks connecting all sectors. The expansion of the bioeconomy can be accelerated through inspiration, opportunities, and support from government initiatives, policies, and funding.

Sustainable development through the bioeconomy is becoming an important policy objective for governments.[81] Some nations are actively making strategies and policies for bioeconomy development and encouraging research.[21,60,84] The European Union has set ambitious targets for bio-based industrial development to mitigate pollution.[85,86] India has partnered with Europe to synchronize efforts to create and facilitate the bioeconomy.[87] The Italian 'Biogasdoneright' movement is an inspiring case of creating a bioeconomy and employment through biorefinery.[42] One of the best-known European rural development programs, LEADER (*Liaison entre actions de développement de l'économie rurale* – meaning 'Links between actions for the development of the rural economy'), was conceived as an integrated and endogenous approach to rural development, achieved success due to its innovative character,[88] and gives hope for small-scale, community-based development of bioeconomy models in rural areas more broadly.

In addition, dedicated international organizations such as BioFuture Platform, FAO-Global Bioenergy Partnership (GBEP), International Sustainable Bioeconomy Working Group (ISBWG), Roundtable on Sustainable Biomaterials (RSB), and International Energy Agency (IEA) are continuously working on developing the bioeconomy for SDGs through collaboration, goal-setting, roadmaps, policy-making, certification, etc.

Besides, nations' other commitments to tackle climate change and pollution are indirectly supportive for promoting bioeconomy development. These include the Paris agreement by 195 nations to mitigate climate change and pollution, the UK's Climate Change Act and declaration of climate emergency, and New Zealand's Climate Change Response (Zero-Carbon) Amendment Act 2019, to nullify the net emission of greenhouse gases by 2050. Many nations are beginning to ban or reduce the use of fossil carbon-derived products such as single-use plastics, and are willing to replace them with bio-based ones.

A comprehensive vision for the development of the bioeconomy

A sustainable world necessitates harmony in and among the citizen, society, and nature. As the bioeconomy is considered crucial for transforming society to meet this goal, it should therefore be carefully designed and developed for (i) building a sustainable economy; (ii) improving the quality of human life; (iii) mitigating negative impacts on the environment, and (iv) conserving biodiversity. The approaches, feedstocks, processes, and products involved should thus be selected or designed considering many factors to satisfy multiple entities.[29]

The development of the sustainable bioeconomy in line with the SDGs may require global participation in innovation and localization of industries with social and environmental benefits while considering competitiveness and costs;[3,21,41] feedstocks, products, and processes that adhere to the principles of green chemistry and green engineering;[35] multifunctional use, reuse, recycling, and waste management practices to minimize net consumption;[24,82] economically viable processes, frugal innovation, and attractive high-quality products to compete with fossil carbon-based industries and satisfy all economic levels in society while minimizing the gaps between them; new chemical transformation methods to supplement or replace many current products;[80] integrating biorefineries with existing fossil carbon-based industries to avoid conflict;[30,89] continuous biomass supply to satisfy the interdependence of supply chains, industries, and jobs;[26] and synergy among biomass types, products, and applications.

Transformation toward a sustainable bioeconomy calls for multidisciplinary, interdisciplinary, and transdisciplinary approaches,[90] so that the best traditions of science and innovation are coupled with systems thinking and systems design, which begins at the molecular level and results in positive global impacts;[35] considerations of human emotions and approaches from the social sciences are integrated with findings from the natural sciences to align human and environmental wellbeing and to strengthen public engagement in collective action to address problems;[91,92] knowledge from diverse subject areas, experts from different fields, and stakeholders from various sectors come together,

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leading to scientific progress, innovation, design, investment, deployment, and development;[3,6,18,21,93] and complex R&D collaborations, social and policy support mechanisms, and financial incentives are simplified and readily accessible to all stakeholders including farmers and rural communities to lower barriers to entry for participation in the bioeconomy.[6,17,94]

Marketing management is also crucial in reducing gaps between innovation and socio-technological transformations. Artificial intelligence (AI) can be significantly helpful in many stages of the bioeconomy. Social media can be used to communicate updates related to biomass production and biorefining. Celebrity promotion can encourage people to engage in the bioeconomy.

Ultimately, scientists, innovators, policymakers, industry leaders, and other stakeholders have a pressing collective responsibility to develop a sustainable bioeconomy to relieve the public of the negative impacts and consequences of their fossil carbon-based lifestyles.

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References

1. United Nations General Assembly, *Transforming Our World: The 2030 Agenda for Sustainable Development*. United Nations, New York (2015). https://sustainabledevelopment.un.org/post2015/transformingourworld/publication.
2. Jackson T, *Prosperity Without Growth? The Transition to a Sustainable Economy*. Sustainable Development Commission, Routledge, London (2009). http://www.sd-commission.org.uk/data/files/publications/prosperity_without_growth_report.pdf.
3. El-Chichakli B, von Braun J, Lang C, Barben D and Philp J, Policy: Five cornerstones of a global bioeconomy. *Nature* **535**:221–223 (2016).
4. Fritsche UR, Eppler U, Fehrenbach H and Giegrich J, *Linkages Between the Sustainable Development Goals (SDGs) and the GBEP Sustainability Indicators for Bioenergy (GSI)*. International Institute for Sustainability Analysis and Strategy (IINAS), Institut für Energie- und Umweltforschung (IFEU), Darmstadt (2018). http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/Indicators/IINAS_IFEU__2018__Linkages_SDGs_and_GSIs_-_final.pdf.
5. Kircher M, Bioeconomy: Markets, implications, and investment opportunities. *Economies* **7**:73 (2019).
6. Bauer F, Coenen L, Hansen T, McCormick K and Palgan YV, Technological innovation systems for biorefineries: A review of the literature. *Biofuels Bioprod Biorefin* **11**:534–548 (2017).
7. Aristizábal-Marulanda V and Cardona Alzate CA, Methods for designing and assessing biorefineries: Review. *Biofuels Bioprod Biorefin* **13**:789–808 (2018).
8. Nilsson M, Griggs D and Visbeck M, Policy: Map the interactions between sustainable development goals. *Nature* **534**:320–322 (2016).
9. Johnson AC, Jin X, Nakada N and Sumpter JP, Learning from the past and considering the future of chemicals in the environment. *Science* **367**:384 (2020).
10. Escher BI, Stapleton HM and Schymanski EL, Tracking complex mixtures of chemicals in our changing environment. *Science* **367**:388 (2020).
11. Waters CN, Zalasiewicz J, Summerhayes C, Barnosky AD, Poirier C, Galuszka A *et al*., The anthropocene is functionally and stratigraphically distinct from the Holocene. *Science* **351**:aad2622 (2016).
12. Díaz S, Settele J, Brondízio E and Ngo HT, *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science- Policy Platform on Biodiversity and Ecosystem Services*. IPBES, Bonn (2019). https://www.ipbes.net/global-assessment-biodiversity-ecosystem-services.
13. Kircher M, The transition to a bio-economy: Emerging from the oil age. *Biofuels Bioprod Biorefin* **6**:369–375 (2012).
14. *World Economic Situation and Prospects* 2019. United Nations, New York, NY (2019). https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/WESP2019_BOOK-web.pdf
15. UNEP, *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication*. UNEP, New york, NY (2011). www.unep.org/greeneconomy.
16. Langeveld JWA, Dixon J and Jaworski JF, Development perspectives of the biobased economy: A review. *Crop Sci* **50**:S-142–S-151 (2010).
17. Dale B, People, planet and profit: Farmers are key to the sustainable bioeconomy. *Biofuels Bioprod Biorefin* **14**:99–100 (2020).
18. Kline KL, Msangi S, Dale VH, Woods J, Souza GM, Osseweijer P *et al*., Reconciling food security and bioenergy: Priorities for action. *GCB Bioenergy* **9**:557–576 (2017).
19. Strengers B and Elzenga H, *Availability and Applications of Sustainable Biomass. Report on a Search for Shared Facts and Views*. PBL Netherlands Environmental Assessment Agency, The Hague (2020). https://www.pbl.nl/en/publications/availability-and-applications-of-sustainable-biomass-report-on-a-search-for-shared-facts-and-views.
20. de Assis CA, Gonzalez R, Kelley S, Jameel H, Bilek T, Daystar J *et al*., Risk management consideration in the bioeconomy. *Biofuels Bioprod Biorefin* **11**:549–566 (2017).
21. Kircher M, The transition to a bio-economy: National perspectives. *Biofuels Bioprod Biorefin* **6**:240–245 (2012).
22. Müller A, Weigelt J, Götz A, Schmidt O, Alva IL, Matuschke I *et al*., *The Role of Biomass in the Sustainable Development Goals: A Reality Check and Governance Implications*. Institute for Advanced Sustainability Studies (IASS), Potsdam (2015). https://gsf.globalsoilweek.org/wp-content/uploads/2015/05/The-Role-of-Biomass_IASS_working_paper.pdf.
23. Alva IL, Beringer T, Goetz A, Matuschke I and Schmidt O, *Sustainable Biomass in the Context of Climate Change and Rising Demand*. Institute for Advanced Sustainability Studies (IASS), Potsdam (2015). https://sustainabledevelopment.un.org/content/documents/6619132-Goetz-Sustainable%20

Biomass%20Production%20in%20the%20Context%20of%20Climate%20Change%20and%20Rising%20Demand.pdf.
24. Bos HL and Broeze J, Circular bio-based production systems in the context of current biomass and fossil demand. *Biofuels Bioprod Biorefin* **14**:187–197 (2020).
25. Daioglou V, Woltjer G, Strengers B, Elbersen B, Ibañez GB, Gonzalez DS *et al*., Progress and barriers in understanding and preventing indirect land-use change. *Biofuels Bioprod Biorefin* **14**:924–934 (2020).
26. Dale BE, Feeding a sustainable chemical industry: Do we have the bioproducts cart before the feedstocks horse? *Faraday Discuss* **202**:11–30 (2017).
27. Michel H, Editorial: The nonsense of biofuels. *Angew Chem Int Ed* **51**:2516–2518 (2012).
28. Markewitz P, Kuckshinrichs W, Leitner W, Linssen J, Zapp P, Bongartz R *et al*., Worldwide innovations in the development of carbon capture technologies and the utilization of CO2. *Energ Environ Sci* **5**:7281–7305 (2012).
29. Gajula S, Antonyraj CA, Odaneth AA and Srinivasan K, A consolidated road map for economically gainful efficient utilization of agro-wastes for eco-friendly products. *Biofuels Bioprod Biorefin* **13**:899–911 (2019).
30. Brown A and Feuvre PL, *Technology Roadmap: Delivering Sustainable Bioenergy*. International Energy Agency, Paris (2017).
31. Dale B, Learning some wisdom from the fracking story? *Biofuels Bioprod Biorefin* **13**:5–6 (2019).
32. Souza GM, Victoria R, Joly C and Verdade L, *Bioenergy & Sustainability: Bridging the Gaps*. Scientific Committee on Problems of the Environment (SCOPE), Paris (2015). http://bioenfapesp.org/scopebioenergy/index.php/chapters.
33. Kulichova ZVDW, Coumou HC, Arujanan M, Wehrmann C and Osseweijer P, The role of scientists in policy-making regarding agricultural biotechnology: From traditional to alternative views. *Int J Biotechnol* **14**:171–190 (2017).
34. Lopes MSG, Engineering biological systems toward a sustainable bioeconomy. *J Ind Microbiol Biotechnol* **42**:813–838 (2015).
35. Zimmerman JB, Anastas PT, Erythropel HC and Leitner W, Designing for a green chemistry future. *Science* **367**:397 (2020).
36. Bridle H, Vrieling A, Cardillo M, Araya Y and Hinojosa L, Preparing for an interdisciplinary future: A perspective from early-career researchers. *Futures* **53**:22–32 (2013).
37. Al-Kodmany K, The vertical farm: A review of developments and implications for the vertical city. *Buildings* **8**:36 (2018).
38. Chalker-Scott L, The science behind biodynamic preparations: A literature review. *Horttechnology* **23**:814–819 (2013).
39. Buehler D and Junge R, Global trends and current status of commercial urban rooftop farming. *Sustainability* **8**:1108 (2016).
40. Orsini F, Kahane R, Nono-Womdim R and Gianquinto G, Urban agriculture in the developing world: A review. *Agron Sustain Dev* **33**:695–720 (2013).
41. Souza GM, Ballester MVR, de Brito Cruz CH, Chum H, Dale B, Dale VH *et al*., The role of bioenergy in a climate-changing world. *Environ Dev* **23**:57–64 (2017).
42. Selvaggi R, Valenti F, Pappalardo G, Rossi L, Bozzetto S, Pecorino B *et al*., Sequential crops for food, energy, and economic development in rural areas: The case of Sicily. *Biofuels Bioprod Biorefin* **12**:22–28 (2018).
43. Savvas D and Gruda N, Application of soilless culture technologies in the modern greenhouse industry - a review. *Eur J Hortic Sci* **83**:280–293 (2018).
44. Gwynn-Jones D, Dunne H, Donnison I, Robson P, Sanfratello GM, Schlarb-Ridley B *et al*., Can the optimisation of pop-up agriculture in remote communities help feed the world? *Glob Food Secur* **18**:35–43 (2018).
45. Pankratz S, Oyedun AO and Kumar A, Development of cost models of algae production in a cold climate using different production systems. *Biofuels Bioprod Biorefin* **13**:1246–1260 (2019).
46. Lakhiar IA, Gao JM, Syed TN, Chandio FA and Buttar NA, Modern plant cultivation technologies in agriculture under controlled environment: A review on aeroponics. *J Plant Interact* **13**:338–352 (2018).
47. Gunning D, Maguire J and Burnell G, The development of sustainable saltwater-based food production systems: A review of established and novel concepts. *Water* **8**:37 (2016).
48. Krebs J and Bach S, Permaculture-scientific evidence of principles for the agroecological design of farming systems. *Sustainability* **10**:3218 (2018).
49. Wartman P, van Acker R and Martin RC, Temperate agroforestry: How forest garden systems combined with people-based ethics can transform culture. *Sustainability* **10**:2246 (2018).
50. Gundekari S, Mitra J and Varkolu M, Chapter 4 - classification, characterization, and properties of edible and non-edible biomass feedstocks, in *Advanced Functional Solid Catalysts for Biomass Valorization*, ed. by Hussain CM and Sudarsanam P. Elsevier, Oxford pp. 89–120 (2020).
51. Kumar M, Sun Y, Rathour R, Pandey A, Thakur IS and Tsang DCW, Algae as potential feedstock for the production of biofuels and value-added products: Opportunities and challenges. *Sci Total Environ* **716**:137116 (2020).
52. Ummalyma SB, Sahoo D and Pandey A, Chapter 12 - microalgal biorefineries for industrial products, in *Microalgae Cultivation for Biofuels Production*, ed. by Yousuf A. Academic Press, London pp. 187–195 (2020).
53. Arevalo-Gallegos A, Ahmad Z, Asgher M, Parra-Saldivar R and Iqbal HMN, Lignocellulose: A sustainable material to produce value-added products with a zero waste approach-a review. *Int J Biol Macromol* **99**:308–318 (2017).
54. Shinde SH, Hengne A and Rode CV, Chapter 1 - lignocellulose-derived platform molecules: An introduction, in *Biomass, Biofuels, Biochemicals*, ed. by Saravanamurugan S, Pandey A, Li H and Riisager A. Elsevier, Cambridge pp. 1–31 (2020).
55. Mikkonen KS, Strategies for structuring diverse emulsion systems by using wood lignocellulose-derived stabilizers. *Green Chem* **22**:1019–1037 (2020).
56. Fiorentino G, Ripa M and Ulgiati S, Chemicals from biomass: Technological versus environmental feasibility. A review. *Biofuel Bioprod Biorefin* **11**:195–214 (2017).
57. Balan V, Jin M and Ubanwa B, 5 - chemical and thermochemical methods on lignocellulosic biorefinery, in *Recent Advances in Bioconversion of Lignocellulose to Biofuels and Value-Added Chemicals within the Biorefinery Concept*, ed. by Ferreira Filho EX, de Souza Moreira LR, Ximenes EA and Farinas CS. Elsevier, Oxford pp. 101–132 (2020).
58. Sun Z, Cheng J, Wang D, Yuan TQ, Song G and Barta K, Downstream processing strategies for lignin-first biorefinery. *ChemSusChem* **13**:5134 (2020).
59. Sharma HK, Xu C and Qin W, Biological pretreatment of lignocellulosic biomass for biofuels and bioproducts: An overview. *Waste Biomass Valor* **10**:235–251 (2017).
60. Balan V, Chiaramonti D and Kumar S, Review of US and EU initiatives toward development, demonstration, and commercialization of lignocellulosic biofuels. *Biofuels Bioprod Biorefin* **7**:732–759 (2013).

  | *Biofuels, Bioprod. Bioref.* **15**:1221–1232 (2021); DOI: 10.1002/bbb.2227

61. Rinaldi R, Jastrzebski R, Clough MT, Ralph J, Kennema M, Bruijnincx PCA *et al*., Paving the way for lignin valorisation: Recent advances in bioengineering, biorefining and catalysis. *Angew Chem Int Ed* **55**:8164–8215 (2016).
62. Patel AK, Dixit P, Pandey A and Singhania RR, Chapter 13 - promising enzymes for biomass processing, in *Biomass, Biofuels, Biochemicals*, ed. by Singh SP, Pandey A, Singhania RR, Larroche C and Li Z. Elsevier, Oxford pp. 245–271 (2020).
63. Arun KB, Madhavan A, Sindhu R, Binod P, Pandey A, Reshmy R *et al*., Remodeling agro-industrial and food wastes into value-added bioactives and biopolymers. *Ind Crop Prod* **154**:112621 (2020).
64. de Schouwer F, Claes L, Vandekerkhove A, Verduyckt J and de Vos DE, Protein-rich biomass waste as a resource for future biorefineries: State of the art, challenges, and opportunities. *ChemSusChem* **12**:1272–1303 (2019).
65. Baghel RS, Mantri VA and Reddy CRK, A new wave of research interest in marine macroalgae for chemicals and fuels: Challenges and potentials, in *Fuels, Chemicals and Materials from the Oceans and Aquatic Sources*. Wiley, Chichester pp. 43–63 (2017).
66. Lakshmi DS, Sankaranarayanan S, Gajaria TK, Li G, Kujawski W, Kujawa J *et al*., A short review on the valorization of green seaweeds and Ulvan: FEEDSTOCK for chemicals and biomaterials. *Biomolecules* **10**:1–20 (2020).
67. Evans J, Building with biosolids. *Biofuels Bioprod Biorefin* **13**:434 (2019).
68. Churkina G, Organschi A, Reyer CPO, Ruff A, Vinke K, Liu Z *et al*., Buildings as a global carbon sink. *Nat Sustain* **3**:269–276 (2020).
69. Ballesteros LF, Michelin M, Vicente AA, Teixeira JA and Cerqueira MÂ, Use of lignocellulosic materials in bio-based packaging, in *Lignocellulosic Materials and their Use in Bio-Based Packaging*. Springer International Publishing, Cham, pp. 65–85 (2018).
70. Ayyachamy M, Cliffe FE, Coyne JM, Collier J and Tuohy MG, Lignin: Untapped biopolymers in biomass conversion technologies. *Biomass Conv Bioref* **3**:255–269 (2013).
71. Ferreira F, Pinheiro I, de Souza S, Mei L and Lona L, Polymer composites reinforced with natural fibers and Nanocellulose in the automotive industry: A short review. *J Compos Sci* **3**:51 (2019).
72. Bilal M, Rasheed T, Nabeel F and Iqbal HMN, Bionanocomposites from biofibers and biopolymers, in *Biofibers and Biopolymers for Biocomposites: Synthesis, Characterization and Properties*, ed. by Khan A, Rangappa SM, Siengchin S and Asiri AM. Springer International Publishing, Cham, pp. 135–157 (2020).
73. Palmeros Parada M, Osseweijer P and Posada Duque JA, Sustainable biorefineries, an analysis of practices for incorporating sustainability in biorefinery design. *Ind Crop Prod* **106**:105–123 (2017).
74. Rebello S, Anoopkumar AN, Aneesh EM, Sindhu R, Binod P and Pandey A, Sustainability and life cycle assessments of lignocellulosic and algal pretreatments. *Bioresour Technol* **301**:122678 (2020).
75. Patel M, Zhang XL and Kumar A, Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: A review. *Renew Sustain Energy Rev* **53**:1486–1499 (2016).
76. Pawelzik P, Carus M, Hotchkiss J, Narayan R, Selke S, Wellisch M *et al*., Critical aspects in the life cycle assessment (LCA) of bio-based materials - reviewing methodologies and deriving recommendations. *Resour Conserv Recycl* **73**:211–228 (2013).
77. Yates MR and Barlow CY, Life cycle assessments of biodegradable, commercial biopolymers-a critical review. *Resour Conserv Recycl* **78**:54–66 (2013).
78. Marques A, Verones F, Kok MTJ, Huijbregts MAJ and Pereira HM, How to quantify biodiversity footprints of consumption? A review of multi-regional input-output analysis and life cycle assessment. *Curr Opin Environ Sustain* **29**:75–81 (2017).
79. Gaur VK, Sharma P, Sirohi R, Awasthi MK, Dussap CG and Pandey A, Assessing the impact of industrial waste on environment and mitigation strategies: A comprehensive review. *J Hazard Mater* **398**:123019 (2020).
80. Funk M and Ash C, A cleaner, greener future for chemicals. *Science* **367**:378 (2020).
81. Zilberman D, Gordon B, Hochman G and Wesseler J, Economics of sustainable development and the bioeconomy. *Appl Econ Perspect Policy* **40**:22–37 (2018).
82. Morone P, The times they are a-changing: Making the transition toward a sustainable economy. *Biofuels Bioprod Biorefin* **10**:369–377 (2016).
83. Bruins ME and Sanders JPM, Small-scale processing of biomass for biorefinery. *Biofuels Bioprod Biorefin* **6**:135–145 (2012).
84. Staffas L, Gustavsson M and McCormick K, Strategies and policies for the bioeconomy and bio-based economy: An analysis of official national approaches. *Sustainability* **5**:2751–2769 (2013).
85. Scarlat N, Dallemand JF, Monforti-Ferrario F and Nita V, The role of biomass and bioenergy in a future bioeconomy: Policies and facts. *Environ Dev* **15**:3–34 (2015).
86. Hassan SS, Williams GA and Jaiswal AK, Lignocellulosic biorefineries in Europe: Current state and prospects. *Trends Biotechnol* **37**:231–234 (2019).
87. Pant D, Misra S, Nizami AS, Rehan M, van Leeuwen R, Tabacchioni S *et al*., Towards the development of a biobased economy in Europe and India. *Crit Rev Biotechnol* **39**:779–799 (2019).
88. Wikipedia contributors, LEADER programme. In: *Wikipedia, the Free Encyclopedia*. (2019). https://en.wikipedia.org/w/index.php?title=LEADER_programme&oldid=913850663
89. Kircher M, The emerging bioeconomy: Industrial drivers, global impact, and international strategies. *Ind Biotechnol* **10**:11–18 (2014).
90. Pfau SF, Hagens JE, Dankbaar B and Smits AJM, Visions of sustainability in bioeconomy research. *Sustainability* **6**:1222–1249 (2014).
91. Shah H, Global problems need social science. *Nature* **577**:295 (2020).
92. Sleenhoff S, Landeweerd L and Osseweijer P, Bio-basing society by including emotions. *Ecol Econ* **116**:78–83 (2015).
93. Economists and scientists: Solve big societal problems by working together. *Nature* **578**:489 (2020).
94. Israël-Hoevelaken BTPM, Wubben EFM, Bos HL, Wijffels RH and Omta OSWF, How to improve the process of forming biobased R&D collaborations. *Biofuels Bioprod Biorefin* **14**:905–923 (2020).

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