ARTICLE IN PRESS

Engineering xxx (xxxx) xxx

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Views & Comments

The Contribution of the Bioeconomy to Sustainable Development

Justus Wesseler [a], Mengshuai Zhu [a,b]

[a] Agricultural Economics and Rural Policy, Wageningen University and Research, Wageningen 6700 HB, the Netherlands
[b] Agricultural Information Institute, Chinese Academy of Agricultural Sciences, Beijing 100081, China

1. The bioeconomy and sustainable development

Over the past decades, significant advances in life science and biotechnology have led policymakers to increasingly prioritize the bioeconomy as a key strategy for addressing global challenges such as food security, healthcare, resource constraints, environmental preservation, and climate change [1,2]. To promote the development of the bioeconomy, the United States released the *National Bioeconomy Blueprint* in 2012 and an executive order on advancing biotechnology and biomanufacturing in 2022, followed by the launching of the National Bioeconomy Board in 2024 [3–5]. China also issued its first bioeconomy plan—*The 14th Five-Year Plan for the Development of the Bioeconomy*—in 2022 [6]. Similarly, the European Union (EU) and several of its member states have endorsed bioeconomy research and policy strategies since 2010. Numerous countries, including India, Brazil, and South Africa, have also implemented bioeconomy policies and strategies to promote sustainability within their economies [1,7].

The concept of the bioeconomy varies in its interpretation and scope. According to the European Commission (EC), the bioeconomy covers "all sectors and systems that rely on biological resources" and all economic and industrial sectors that "produce food, feed, bio-based products, energy, and services" [8]. The US Department of Agriculture (USDA) defined the term "bio-based product" in the *Farm Security and Rural Investment Act of 2002* as "a commercial or industrial product (other than food or feed) that is composed in whole or in significant part of biological products or renewable domestic agricultural materials (including plant, animal, and marine material) or forestry material" [9]. These definitions of bioeconomy share many similarities. Agriculture, forestry, fisheries, food, pulp and paper production, and parts of the chemical, biotechnological, and energy industries are all considered part of the bioeconomy, from a sectorial perspective on the measurement of the bioeconomy [1]. Moreover, the view on the bioeconomy goes beyond the sectorial. The generation of knowledge for developing new solutions to address the challenges mentioned above is important in the bioeconomy, as is the development of new business models for a circular bioeconomy, which has recently gained attention.

The bioeconomy acts as a key driver of sustainable development by sustainably utilizing biological resources and biological knowledge, thereby enhancing social, economic, and environmental well-being [10,11]. The action plan of the EU's bioeconomy strategy aligns with 53 targets across 12 of the 17 Sustainable Development Goals (SDGs) [12]. The bioeconomy can have substantial impacts, which are effectively reflected in the broad range of SDGs [13]. Monitoring and evaluating the bioeconomy can help track progress on SDGs, especially in areas such as economic growth (SDG 8), food security (SDG 2), and sustainable consumption (SDG 12) [11].

The bioeconomy differs from related concepts associated with sustainable development [14,15], such as the "bio-based economy," "green economy," and "circular economy." These terms often intersect and share common goals related to sustainability and resource efficiency. The green economy is often considered an overarching concept aimed at improving human well-being and social equity and reducing environmental risks and ecological scarcity. The bioeconomy is generally viewed as a subset of the green economy that focuses on economic growth and technological development through the sustainable use of biological resources and biological knowledge. A bio-based economy is a concept that focuses on manufacturing and involves converting biological resources into products and materials, including both innovative bio-based products and traditional ones such as textiles and wood products. The circular economy, complementary to the bioeconomy, emphasizes recycling, reduction, and sustainable resource use to minimize waste and aims to provide sustainable wellbeing through the provision of ecosystem services and the sustainable management of biological resources. The synergies between the bioeconomy and circular economy concepts are significant. Bioeconomy can be considered the renewable part of the circular economy. The term "circular bioeconomy," which has been introduced by the EC and others, highlights the integration of both concepts and emphasizes the importance of applying circular principles to the bioeconomy [14].

The bioeconomy involves various interconnected factors and participants, including driving forces, resource utilization, policies, strategies, legislation, and societal goals, all linked through biomass supply and usage and biological knowledge [14]. Supply and demand are essential in shaping this system. The availability of resources, such as land, water, and labor, significantly affects the biomass market. Additionally, waste and byproducts are crucial for a sustainable and circular bioeconomy. Government policies, strategies, and legislation influence the bioeconomy. The

https://doi.org/10.1016/j.eng.2024.08.019

Please cite this article as: J. Wesseler and M. Zhu, The Contribution of the Bioeconomy to Sustainable Development, Engineering, https://doi.org/10.1016/j.eng.2024.08.019

interaction of these driving forces, resources, and policies impacts the bioeconomy's supply and demand, supporting its contribution to sustainable objectives.

2. Measuring the contribution of the bioeconomy to sustainable development

Measuring the contribution of the bioeconomy to economic growth and sustainable development is challenging due to the bioeconomy's dynamic nature, which is affected by technological advancements, industrial progress, policy shifts, and other factors. Numerous projects and methodologies have provided valuable insights and results.

2.1. Bioeconomy value added and turnover

In order to measure the contribution of the bioeconomy to economic growth, it is necessary to understand its share within the overall economy. One widely used approach relies on the system of national accounts, while input−output tables and statistical surveys are also commonly employed [16,17]. Based on MAGNET, a global forward-looking *ex-ante* simulation model, the BioMonitor project of the European Union's Research and Innovation Funding Programme Horizon 2020[†] bridged the information gap in bioeconomy research by restructuring its existing data and modeling framework and projected the EU bioeconomy production trends. The project introduced new biochemical activities (biochemicals, biopharmaceuticals, and bioplastics) to create a new virtual trade and a "footprints" module with a state-of-the-art baseline.

Using 2020 as the base year, significant increases are anticipated in 2030 and 2050 across all relevant sectors in the EU. The total bioeconomy production is estimated to be about 3295 million EUR in 2020, 3647 million EUR in 2030, and 4234 million EUR in 2050. The largest subsector is food and food services, with estimated values of about 1576 million EUR in 2020, 1786 million EUR in 2030, and 2172 million EUR in 2050. The "biofuel-solid" sector shows the most significant change, nearly doubling by 2050 in comparison with 2020.

BioMonitor also analyzed scenarios in which fossil fuel prices rise by 30% (30% case) and 50% (50% case) above the baseline in 2050, projecting both positive and negative impacts. In the baseline scenario, the real Gross Domestic Product (GDP) is projected to reach 160% in 2050, with the base year set at 2020 (= 100%). However, in the 30% case, the real GDP is expected to decrease by 0.47% and, in the 50% case, by 0.74%. On the positive side, the EU's total emissions ($MtCO_2e$) for 2050 are projected to be 2628 Mt CO_2 equivalents. Nevertheless, in both the 30% and 50% cases, emissions are forecasted to decrease, with reductions of about 227 and 348 Mt CO_2 equivalents, respectively.

2.2. The Joint Research Center (JRC) bioeconomy monitoring system

The JRC of the EC created the BMS-Job&Growth dataset to monitor the socioeconomic aspects of the EU's bioeconomy. The dataset integrates various data sources, such as national accounts, expert knowledge, and industrial statistics. After pre-processing the data, experts' opinions are used to determine the bio-based shares. Key indicators of the system include employment numbers, turnover, value added, location quotient, and labor productivity in the bioeconomy sectors [18].

The results show that the bioeconomy in the EU27 member states employed 17.19 million people in 2021, with over half being in primary sectors and more than a quarter in the sector of food, beverages, and tobacco. The total bioeconomy generated 728 billion EUR, including 235 billion in primary sectors and 262 billion in the food, beverages, and tobacco sector. Germany had the highest bioeconomy value added, at approximately 135 billion EUR, followed by France (111 billion EUR), Italy (99 billion EUR), and Spain (75 billion EUR)[‡]. The bioeconomy also showed significant growth potential, driven by advancements in biotechnology and increased investments in sustainable practices. Furthermore, emerging sectors such as bio-based chemicals and bioenergy are expected to contribute substantially to future economic and employment growth in the EU bioeconomy.

2.3. The material flow model

Modeling results can be linked to material flow models and vice versa. A material flow model is a tool that helps analyze how materials move through different processes within a system. The flow model is a vital tool for advancing the bioeconomy by promoting efficient resource use, supporting sustainable practices, and guiding informed decision-making. By integrating data on inputs, processing, outputs, transportation, and inventories, the flow model provides information on resource efficiency. It also identifies areas for efficiency improvement and assesses environmental impacts. Moreover, it evaluates recycling strategies and waste management and helps plan logistics for material distribution.

The Netherlands serves as an illustrative example [19]. In 2018, the Dutch economy utilized nearly 450 Mt of material resources, comprising primary resources, recycled materials, and recycled materials within materials, components, and products. Approximately a quarter originated from domestic sources, such as natural gas, gravel, and agricultural products, while the remaining three-quarters were sourced from abroad, including fossil fuels, metals, and materials within products. Nearly half of these material resources were exported as finished or semi-finished products, such as fodder converted into meat or metals processed into machine parts. In addition, the Netherlands imported a significant volume of material resources, which were largely re-exported to other countries without substantial processing.

2.4. Bio-based material availability

Material flow models are of particular interest for modeling bio-based materials used in the chemical and construction sector. Measuring bio-based material production is also essential for assessing the potential of the bioeconomy. BioMAT (Bio-based MATerials) is a new consistent framework that aims to provide projections for the markets of bio-based materials, starting with bio-based chemicals, and for the respective feedstock needs for EU member states and the EU27, up to 2030 and 2050. BioMAT operates as a module of AGriculture MEmber state MODeling (AGMEMOD), focusing on the chemical industry (sector code in national accounting: C20) with full coverage of all bio-based products. It starts with production data of manufactured goods carried out by enterprises on the national territory of the reporting country (PRODuction COMmunautaire codes) and offers a stylized representation of value chains. The illustrative example groups the entire output of C20 into 16 product application categories, including two intermediates. In addition, BioMAT differentiates between ten types of bio-based feedstocks and links them to agricultural crop production in the EU via linkage to AGMEMOD [20,21]. The production of bio-based chemicals in the EU amounted to 43 million metric tonnes in 2018, accounting for 14% of the total output volume of the organic chemical industry. BioMAT breaks down how these materials were used,

[†] https://biomonitor.eu/.

[‡] https://datam.jrc.ec.europa.eu/datam/mashup/BIOECONOMICS/.

with biofuels being the biggest category (42%), followed by agrochemicals (21%), surfactants (12%), and cosmetics and personal care products (6%). Other uses make up smaller portions [20].

3. Future opportunities and challenges

Innovative technologies are reshaping the bioeconomy. Through biotechnology, microorganisms are being engineered to produce biofuels and bioplastics sustainably. Precision agriculture employs global positioning systems (GPS) and drones for efficient farming, while advanced biomaterials replace traditional plastics, reducing reliance on fossil fuels. Bioremediation utilizes microorganisms to clean up pollutants, and cellular agriculture grows meat in labs, offering a sustainable alternative. Urban fishermen are adopting aquaponics for fish cultivation. Insect burgers provide a protein-rich and eco-friendly food option. Biological carbon capture harnesses algae to convert CO_2 into valuable products, while microbial electrochemical technologies generate energy from organic waste, driving both environmental protection and economic growth. Industrial hemp production provides opportunities for net-zero carbon building materials. These technologies are not only helping to protect the environment but also creating new economic opportunities in the bioeconomy. These are only a few illustrative examples; many more examples exist.

Some top research questions, such as net-zero solutions, require cooperation among scientists, engineers, and policymakers. These questions involve investigating the most promising technological innovations across various sectors while addressing intellectual property rights and regulatory issues to incentivize dissemination. Monitoring tools at the national and international levels necessitate identifying key indicators and improving data analytics for accurate progress tracking, alongside establishing governance mechanisms for transparency. Harmonizing national and international policies requires resolving gaps and overlaps, designing multi-level governance frameworks, and leveraging international organizations to promote coherence. This entails reconciling divergent interests, standardizing policy instruments, and overcoming political and institutional barriers through capacity-building and diplomatic negotiations.

References

[1] Wesseler J, von Braun J. Measuring the bioeconomy: economics and policies. Annu Rev Resour Econ 2017;9:275–98.

[2] Zilberman D, Gordon B, Hochman G, Wesseler J. Economics of sustainable development and the bioeconomy. Appl Econ Perspect Policy 2018;40 (1):22–37.

[3] The White House. National bioeconomy blueprint. Washington DC: The White House; 2012.

[4] The White House. Executive order on advancing biotechnology and biomanufacturing innovation for a sustainable, safe, and secure American bioeconomy. Washington DC: The White House; 2022.

[5] The White House. The White House advances biotechnology and biomanufacturing leadership with the launch of the national bioeconomy board. Washington DC: The White House; 2024.

[6] National Development and Reform Commission of China. The 14th Five-Year Plan for the Development of the Bioeconomy. Beijing: National Development and Reform Commission of China; 2022.

[7] Dietz T, Börner J, Förster JJ, von Braun J. Governance of the bioeconomy: a global comparative study of national bioeconomy strategies. Sustainability 2018;10(9):3190.

[8] European Commission. A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment : updated bioeconomy strategy. Luxembourg: Publications Office of the European Union; 2018.

[9] Office of Energy Policy and New Uses, Office of the Chief Economist. US Biobased products market potential and projections through 2025. Washington DC: US Department of Agriculture; 2008.

[10] Ferraz D, Pyka A. Circular economy, bioeconomy, and sustainable development goals: a systematic literature review. Environ Sci Pollut Res 2023;30(47).

[11] Calicioglu Ö, Bogdanski A. Linking the bioeconomy to the 2030 sustainable development agenda: Can SDG indicators be used to monitor progress towards a sustainable bioeconomy? N Biotechnol 2021;61:40–9.

[12] Ronzon T, Sanjuán AI. Friends or foes? A compatibility assessment of bioeconomy-related sustainable development goals for European policy coherence. J Clean Prod 2020;254:119832.

[13] Heimann T. Bioeconomy and SDGs: does the bioeconomy support the achievement of the SDGs? Earths Futur 2019;7(1):43–57.

[14] Kardung M, Cingiz K, Costenoble O, Delahaye R, Heijman W, Lovrić M, et al. Development of the circular bioeconomy: drivers and indicators. Sustainability 2021;13(1):413.

[15] D'Amato D, Korhonen J. Integrating the green economy, circular economy and bioeconomy in a strategic sustainability framework. Ecol Econ 2021;188:107143.

[16] Heijman W. How big is the bio-business? Notes on measuring the size of the Dutch bio-economy. Njas-wagen J Life Sc 2016;77:5–8.

[17] Efken J, Dirksmeyer W, Kreins P, Knecht M. Measuring the importance of the bioeconomy in Germany: concept and illustration. Njas-wagen J Life Sc 2016;77:9–17.

[18] Lasarte-López J, M'Barek R, Ronzon T, Tamosiunas S. EU bioeconomy monitoring system indicators update: jobs and value added in the EU bioeconomy 2020. Luxembourg: Publications Office of the European Union; 2023.

[19] Lucas P, Brink H, van Oorschot M. Addressing international impacts of the Dutch circular economy transition. The Hague: PBL Netherlands Environmental Assessment Agency; 2022.

[20] Sturm V, van Leeuwen M, Gonzalez-Martinez A, Verhoog D, Hark N, de Beus N. Providing insights into the markets for bio-based materials with BioMAT. Sustainability 2023;15(4):3064.

[21] Van Leeuwen M, Gonzalez-Martinez AR, Sturm V. Developing BioMAT: a new conceptual framework to model the market of bio-based materials in the EU. Stud Agric Econ 2022;124(2):82–7.