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Article

Assessing the contribution of bioeconomy to the total economy: a review of national frameworks

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Abstract: Developments in technology have enabled envisioning the derivation of materials and products from renewable biomass, as an alternative to finite fossil-based resource consumption. Therefore, bioeconomy is regarded as an opportunity for sustainable economic growth. Countries are formulating strategies in accordance with their goals to attain from bioeconomy. Proper measurement, monitoring and reporting of the outcomes of these strategies is crucial for long-term success. This study aims to critically evaluate the national methods used for the measurement, monitoring and reporting of bioeconomy contribution to the total economy. For this purpose, research and surveys have been conducted on selected countries (Argentina, Germany, Malaysia, the Netherlands, South Africa and the United States). The results reveal that the bioeconomy targets set up in the strategies often reflect country's priorities and comparative advantages. However, comprehensive approaches to measure and monitor bioeconomy progress are frequently lacking. Most countries only measure the contribution to gross domestic product (GDP), turnover and employment of the sectors included in their bioeconomy definition, which may provide an incomplete picture. In addition, this study identifies the mismatch between the targets and measurement methods, as the environmental and social impacts of bioeconomy are often foreseen, but not measured. It is concluded that existing global efforts towards a sustainable bioeconomy monitoring can be strengthened and leveraged to measure progress towards sustainable goals.

Keywords: Bioeconomy; Bio-based products; GDP; Policy measures; Sustainability assessment; Sustainable development

1. Introduction and background

Modern economies rely on resources which are finite in nature. On top of their long-term unsustainability, utilization of fossil fuel resources and unsustainable consumption of derived products also pose risk to societies and the environment due to their negative impacts such as climate change and ecosystem degradation [1,2]. Nevertheless, advancements in industrial biotechnology have enabled derivation of materials, chemicals and energy from renewable biomass, which could provide substitutes over fossil-based and finite resources [3]. This substitution potential forms the core of a still-evolving bioeconomy concept.

The literature on bioeconomy vision has been evolving in parallel to the concept, and has been clustered under three major perspectives: (1) the biotechnology vision which emphasizes innovations and utilization of biotechnology at commercial scales; (2) the bioresource vision emphasizes the improvement of value chains on upstream biomass production; (3) the bioecology vision which emphasizes the positive impacts of energy and resource optimization on ecosystem health [4]. These perspectives underline the potential of bioeconomy in the opportunities it offers, such as low-carbon

economic growth, preservation of natural resources, restoration of environmental and ecosystem health, and welfare of rural communities.

Due to its promising potential in addressing these global challenges, bioeconomy has been directly or indirectly included in the policy agendas worldwide [5,6]. Country objectives and bioeconomy priorities encompass economic growth, employment, energy security, food security, fossil fuel reduction, mitigation and adaptation to climate change, and rural development [7]. With respect to their potentials in deploying the bioeconomy vision, countries have different opportunities, which might also affect their policies. Countries can be classified as countries with (1) an abundance of renewable biological resources, but a lack of downstream processing industries, (2) both high feedstock potential and advanced processing industries, and (3) low feedstock potential but advanced processing industries [8]. These variations in the potential also create differences in countries' objectives for adopting a bioeconomy strategy and in the evaluation of success towards their achievement.

Measuring bioeconomy contribution to countries' overall economy can be an important indicator of development. No internationally agreed methodology exists today to measure progress in attaining the ambitions and targets set by bioeconomy policies and strategies. Moreover, given the differences between countries' constraints, opportunities and priorities, the development of a uniform way to assess the contribution of bioeconomy to the national economy is challenging. This lack of a coherent methodology could create confusion when trying to compare the importance of bioeconomy within and across countries. One first step towards a globally recognized methodology could be to assess the current efforts of individual countries to define bioeconomy, and the frameworks for measuring, monitoring and reporting its contribution.

Typical economic models that can be adopted to measure the bioeconomy contribution to a country's economy include the value added/GDP approach; Input-Output (I-O) and Social Accounting Matrix (SAM) analysis; Computable General Equilibrium (CGE) Model; Partial Equilibrium (PE) Model and other economic models and tools [9]. However, these approaches do not systematically consider environmental and social aspects. In fact, the objective of this study is to analyse how the contribution of bioeconomy is measured in the overall national economy, using information from a geographically representative list of countries (Argentina, Germany, Malaysia, the Netherlands, South Africa and the United States). Furthermore, the alignment of the country objectives and the parameters measured have been analysed, in order to assess whether social and environmental impacts of bioeconomy were captured through selected measurement, monitoring and reporting frameworks adopted by the countries.

Within the scope of this study, the bioeconomy has been defined as "the knowledge-based production and utilization of biological resources, biological processes and principles to sustainably provide goods and services across all economic sectors" development [7]. It involves three elements: (1) The use of renewable biomass and efficient bioprocesses to achieve a sustainable production; (2) The use of enabling and converging technologies, including biotechnology; (3) Integration across applications such as agriculture, health and industry. In accordance with the Food and Agriculture Organization of the United Nations (FAO) development [7], the term "bio-based economy" excluded the food and feed production. Instead, it was used to take the production of non-food goods into consideration; i.e. bio-based materials, chemicals, and pharmaceuticals; pulp and paper; construction materials; textiles; and bioenergy. "Bio-based industry" refers to the industrial production of all possible bio-based goods. The strategies related to bioeconomy, bio-based economy and bio-industries were all considered as "bioeconomy strategies". This assessment has been built upon previous and ongoing efforts to foster global bioeconomy. In this respect, the countries to be investigated have been selected among the members of the FAO International Sustainable Bioeconomy Working Group (ISBWG), which includes 23 members as of March 2018: 11 countries (Argentina, Brazil, China, Germany, Italy, Kazakhstan, Malaysia, the Netherlands, South Africa, Uruguay and United States), the German Bioeconomy Council, the European Union (EU) Commission, Organisation for Economic Co-operation and Development (OECD), International Center for Tropical Agriculture (CIAT), Stockholm Environment Institute (SEI), United Nations

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Environment Programme (UNEP), World Wide Fund (WWF), the Nordic Council of Ministries, the EU Bio-Based Industries Consortium, Wageningen University, the World Business Council for Development (WBCSD) and FAO.

The countries selected for the study are located in five continents, differ in terms of level of economic development and have different bioeconomy strategies and priorities. For instance, some countries have little land availability but advanced technologies, while others prioritize farmers and rural development and have greater land availability. For all the countries, the study reviews bioeconomy objectives and priorities as well as measurement, monitoring and reporting frameworks. From the sample countries and a review of existing literature, a pathway towards a sustainable bioeconomy monitoring is then proposed.

2. Approach and Methods

The study was based on desk research of policy documents, strategies and statements on the bioeconomy and its measurement for a selected number of countries (Argentina, Germany, Malaysia, the Netherlands, South Africa and the United States). Because of their demonstrated interest in developing a global bioeconomy framework, the selection process was primarily performed among the ISBWG member countries, following the selection process illustrated in Figure 1. The structural organization of the analysis included an evaluation of the available information in terms of: (1) how countries define bioeconomy; (2) which are the objectives and/or priorities of their strategy; (3) the methodology they use to measure, monitor and report the contribution of bioeconomy to their economy or objectives (**Figure 1.**).

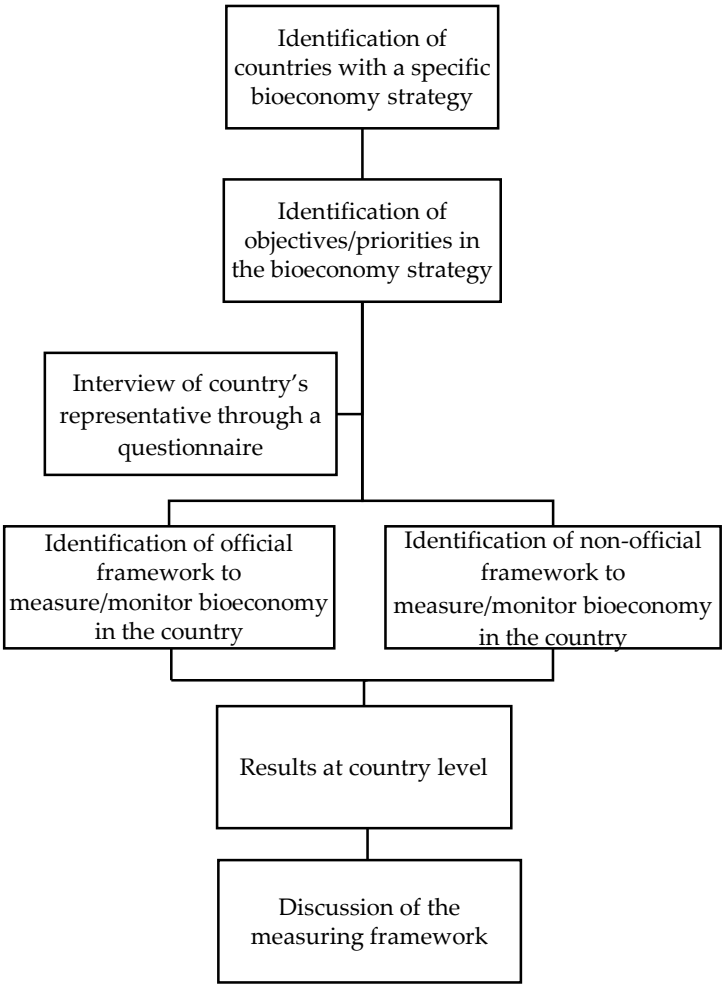

Figure 1. Selection process and structural organization of the analysis

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The relevant information for the analysis was gathered from official bioeconomy strategies and documents, upon availability. When a government official document on how to measure the contribution of bioeconomy to the total economy was not available, commissioned studies, studies from research institutes and/or non-profit organizations were used instead. Table 1 summarizes the sources of information and documents analysed in order to understand the definition of bioeconomy, the objectives/priorities of the bioeconomy strategy, and the measurement, monitoring and reporting frameworks established by each selected country. Whenever possible, the information was complemented and validated by a survey, distributed to government representatives (Table 2). The survey included the same questions to which answers were sought while scanning through the written materials.

Table 1. Sources of information for the selected countries.

	Bioeconomy definition and strategy	**Objectives/ priorities of the strategy**	**Measurement, monitoring and reporting framework**
Argentina	Ministry of Agroindustry (MINAGRO) [10]	MINAGRO [10]	Bolsa de Cereales [11]
Germany	Federal Ministry of Food and Agriculture (BMEL), and the Federal Ministry for Education and Research (BMBF) [12]	National Policy Strategy on Bioeconomy [13]	A comprehensive and system monitoring approach to measure the contribution of German BE to the overall economy is currently under development
Malaysia	National Biotechnology Policy (NBP); the BioNexus Status (BNX); the Bioeconomy Transformation Programme (BTP); the Bioeconomy Community Development Programme (BCDP); National Biomass Strategy 2020 ("NBS 2020") [14]	BTP and BCDP [14]	MOSTI and Bioeconomy Corporation ([14], [15])
The Netherlands	Netherlands Enterprise Agency (RVO) [16]; CE Delft [17]; Agency Ministry of Economic Affairs (NOST) [18]; NNFCC [19]	NOST [18]; NNFCC [19]	Bio-based economy protocol monitor [16]; NOVA Institute [20]; CE Delft [17]; EC Bioeconomy Knowledge Centre [21]
South Africa	Public Understanding of Biotechnology [22]; National Biotechnology Strategy [23]	National Biotechnology Strategy [23]	National Biotechnology Strategy [23]; ongoing study to establish a framework to develop indicators to measure the growth of the BE in South Africa [24]
USA	National Bioeconomy Blueprint [25]; The Billion Ton Bioeconomy Vision [26]	National Bioeconomy Blueprint [25]; The Billion Ton Bioeconomy Vision [26]	USDA reports ([27–29]); Department of Energy [30]

Information collected through desk research and surveys has been used for the analysis and has been complemented with an extensive literature review of objectives and priorities of bioeconomy strategies in other low, middle and high income countries (outside the study focus) in order to improve the quality of the discussion. For this purpose, the survey was distributed to all ISBWG members (not only to those in the study focus).

Table 2. Questionnaire submitted to ISBWG members on assessing bioeconomy contribution to countries' economy

Bioeconomy definition
How does your Country define bioeconomy?
Which sectors are included into your bioeconomy strategy? (e.g. Agriculture; Automotive and mechanical engineering; Chemistry (incl. bioplastics); Biofuels/bioenergy; Biorefining; Construction/Building industry; Consumer goods such as cosmetics and cleaning products; Feed; Fisheries; Food and Beverage industry; Forestry; Health; Knowledge/Innovation; Mining; Pharmaceuticals industry; Pulp and paper; Textiles)
Objectives/priorities
Which are the objectives/priorities of your country strategy (e.g. food security, energy security, fossil fuel reduction, rural development, economic growth, employment, mitigation and adaptation to climate change, etc.)?
Measurement, monitoring and reporting framework
Does the country strategy include criteria to measure the contribution of bioeconomy to the overall economy? If yes, which ones?
Which approach does your country use to measure bioeconomy contribution? (e.g. GDP approach; Input-Output matrix; Computable General Equilibrium (CGE) Model; Partial Equilibrium (PE) Model)
Does your country measure the impact of bioeconomy on the following areas? (Turnover/sales; Value added; Job creation; Market development; Investments; Intellectual property; R&D spending; Trade balance; Poverty alleviation; Food security and sustainable agriculture; Health and well-being; Education; Gender equality; Availability and sustainable management of water; Access to affordable, reliable, sustainable and modern energy; Inclusive and sustainable industrialization and innovation; Inequality and inclusiveness; Inclusive, safe, resilient and sustainable cities; Ensure sustainable consumption and production patterns; Climate change; Oceans, seas and marine resources; Terrestrial ecosystems, forests, land degradation and biodiversity)
Are indicators to measure bioeconomy contribution defined? If so, which ones?
Short discussion
Which is, in our opinion, the main limitation of your country approach to measure bioeconomy contribution?

3. Analysis and Results

3.1. Bioeconomy definitions and strategies

It is observed that the sectors and sub-sectors considered in 'bioeconomy' were different among the analysed countries, which is a reflection of the differences in their priorities and strategies. Table 3 summarizes the various sectors included in the bioeconomy definition by the six analysed countries, and the sectors taken into account for the quantification of bioeconomy contribution to overall national economy. The first important point is the variation in the definition of bioeconomy. For instance, the Netherlands has a focus on *bio-based economy*, excluding the agriculture and food sectors [17] and still has not agreed on a which sectors are included in the bioeconomy [31]. The United States aims to analyse the bioeconomy, but USDA shows results limited to *bio-based products industries*, which exclude the energy, food, feed, livestock, and pharmaceutical industries.

According to Argentina, the bioeconomy includes agriculture, forestry, fishing, food production and pulp and paper production, as well as parts of textile, chemical, energy and biotechnological

industries (medical and pharmaceutical industry). The German bioeconomy includes agriculture, forestry, fishing, manufacturing and trading of bio-based products. Similarly, the Malaysian bioeconomy includes agriculture, forestry, fisheries, food, feed, healthcare wellness products, chemicals and renewable energy. South Africa's bioeconomy strategy focuses on agriculture, industrial and environmental bio-innovation and health, but has yet to develop metrics to monitor performance.

Table 3. Sectors included into BE strategy and monitoring in the selected countries

	Argentina	Germany	Malaysia	Netherlands*	South Africa	USA*
Agriculture	■■	■■	■■		■	■■
Automotive and mechanical engineering		■■				
Chemistry (incl. bioplastics)	■■	■■	■■	■■	■	■■
Biofuels/bioenergy	■■	■■	■■	■■	■	
Biorefining		■■	■■		■	■■
Construction/Building industry		■■				
Consumer goods (e.g. cosmetics, cleaners)	■■	■■			■	
Feed	■■	■■	■■		■	
Fisheries	■■	■■	■■		■	
Food and Beverage industry	■■	■■	■■		■	
Forestry	■■	■■	■■	■■**	■	■■
Health			■■		■	
Knowledge/Innovation		■■	■■	■■	■	
Mining					■	
Pharmaceutical industry	■■	■■	■■	■■	■	
Pulp and paper	■■	■■		■■	■	
Textiles	■■	■■		■■	■	■■
References:	[11]	[12]	[32]	[20]	[33,34]	[29]

*The monitoring system analysis for the Netherlands refer to bio-based economy and the results for the US refer to bio-based products industries. ** Only forest-based industry.

Legend: ■- included in bioeconomy strategy, ■■- included in the bioeconomy strategy and monitored or measured.

It is worthwhile to note that the decision on which sectors to include is also relevant when trying to measure the bioeconomy's contribution to countries' economies in terms of GDP and value added, since the calculations would only take the included sectors into account [35].

3.2. Bioeconomy objectives and priorities

The sectors included in the bioeconomy strategy often reflect the priorities identified by the country and comparative advantages linked for instance to endowment in biomass resources, historical economic specialization, labour productivity and past investments in R&D [7,11,36–40].

For instance, in Argentina, bioeconomy is seen as a tool for sustainable development in the country. It is recognized as a positive alternative for the generation of new behaviours and sources of employment to face the double challenge of climate change and the continued need for economic progress indispensable for poverty reduction [10].

In Germany, the National Policy Strategy on Bioeconomy's priorities for advancing towards a knowledge-based bioeconomy are: the development of a secure supply of high-quality food; the transition from a fossil-based economy to an economy that is increasingly efficient in terms of raw materials and based on renewable resources; the supply of renewable resources; the sustainable use of renewable resources while conserving biodiversity and soil fertility; protection of the climate; strengthening of Germany's innovative power and its international competitiveness in business and research; securing and creating employment and added value, particularly in rural areas; and sustainable consumption [13].

In Malaysia, bioeconomy is seen as a key contributor to economic growth, which can provide benefits to the society via breakthroughs in agricultural productivity, innovations in healthcare and the adoption of sustainable industrial processes [15].

The objectives of the South African bioeconomy strategy are to make the country more competitive internationally (especially in the industrial and agriculture sectors); to create more sustainable jobs; to enhance food security; and to create a greener economy as the country shifts towards a low-carbon economy [23]. In particular, the strategic economic sectors identified are i) agriculture, ii) health and iii) industry and environment.

In the Netherlands, the bioeconomy strategy encourages knowledge development and innovation in nine top sectors: agriculture and food, water, chemicals, energy, life sciences and health, horticulture and propagation materials (seed stock), logistics, high-tech systems and materials and creative industries [18]. However, the Dutch government focuses more often on the bio-based economy, defined as "economic activity based on biomass, with the exception of human food and feed", with the condition that it is based on recently captured carbon [41]. The most important drivers behind the adoption of a bio-based economy strategy were: striving for more sustainability (reduction of CO_2 emissions, circular economy); the awareness of the finite nature of fossil fuels, and the economic opportunities offered to Dutch businesses through the use of renewable biological resources and residues [18].

In the USA, the five strategic objectives introduced by the National Bioeconomy Blueprint aimed to generate economic growth and address societal needs. Some of these strategies include supporting R&D investments, facilitating the transition of bio-inventions from research lab to market, developing and reforming regulations, updating training programmes, and aligning academic institution incentives with student training for national workforce needs. They also include identifying and supporting opportunities for the development of public-private partnerships and precompetitive collaborations in their objectives [25].

3.3. Measurement, monitoring and reporting frameworks

The countries selected for the study use various approaches for measuring bioeconomy contribution to their economy and in attaining the objectives.

In the case of Argentina, a standard approach was adopted to measure the contributions (gross production value and value added) of bio-based products to the national GDP, referencing the general principles of the System of National Accounts (SNA) for the calculation of GDP and internationally comparable satellite accounts (e.g. for education, capital, productivity and environment). A paper by the an intermediate service provider *Bolsa de Cereales* [11] designs a general methodology for the criteria, procedures, and database to be used in the measurement of bioeconomy and its contribution to GDP. The sectors included in the calculation of the bioeconomy's contribution to the GDP are: "agriculture, forestry, fishing, food production and pulp and paper production, as well as [bio-based] fractions of textile and chemical industry, and energy and biotechnological industries (health and pharmaceutical industry)" [11], in alignment with the sector included in the country's bioeconomy strategy.

In Germany, most of the areas contributing to bioeconomy are monitored by traditional statistical accounts [12]. However, in most of the cases, methodologies for data collection and assessment are not streamlined to assess the impact of the bioeconomy. This leads to sparse information on impacts, along with data gaps, uncertainties, lack of comparability of results and potentially double-counting of impacts. A comprehensive and system monitoring approach to measure the contribution of German bioeconomy to the overall economy is currently under development by a joint inter-ministerial undertaking, made of three main projects: the monitoring of biomass flows, the Systemic Monitoring and Modelling of the Bioeconomy (SYMOBIO) and the identification of economic key performance indicators to monitor the bioeconomy [42].

Malaysia has developed a Bioeconomy Contribution Index (BCI) to measure the contribution of bioeconomy to the overall economy, which is a combination of five components/parameters: bioeconomy value-added, bio-based exports, bioeconomy investments, bioeconomy employment, and productivity performance [14]. The BCI is a comparative tool designed to provide a holistic view, encompassing multiple aspects of the bioeconomy, and it is used to identify trends, patterns and synergies within the industry. The index compares the performance of each specific component for a

selected year against the adjusted (i.e., accounting for changes in variables such as inflation rates, import-export values) expected base performance (in the base year 2005), determined by a Dynamic Computable General Equilibrium (DCGE) model [15]. The share of bioeconomy contribution to national development is estimated from the SAM, assuming that Malaysia is a price taker country [43].

Since the Netherlands lacks a clear protocol on defining the boundaries of the bioeconomy, until now their focus has been on the bio-based economy (BBE). In 2013, the Netherlands established a BBE monitoring protocol to quantify its size, and to monitor its development over time, in order to make trends visible, and comparable with developments abroad [16]. The protocol defines the system boundaries, the units to express the size of BBE, and utilization of available data or their collection, if missing. The protocol is built on existing statistical data on production and consumption, prevents double-counting of bio-based raw materials and accounts for raw material flows monitoring. However, it raises some problems linked to classification of business sectors, classification of product groups, and timely acquisition of data [16].

The South African bioeconomy strategy [23] contains some indicators to monitor progress in the bioeconomy in comparison with other high and middle-income countries, broadly divided into "knowledge and skills" indicators (full-time equivalent researchers, scientific publications, bioeconomy-related publications) and "financial support" indicators (gross domestic expenditure on R&D as percentage of GDP; funding and governmental support). Moreover, the methodology provides eighteen output indicators (related to industry; market; knowledge transmission and application; and knowledge base and human resources) to be used to track and monitor the bioeconomy strategy [23]. However, systematic metrics to measure and monitor South Africa's bioeconomy have not yet been implemented. Ongoing efforts are anticipated to result in detailed implementation plans and value propositions for specific sectors and initiatives that will help refine targets [34].

The USDA report [29] examines and quantifies the effect of the bio-based products industry from an economics and jobs perspective at the state level. It was preceded by a report analysing the effect at national level [28] and by another report [44] which provides a snapshot of available information on the bioeconomy in the country and a platform upon which to build future efforts to measure the bioeconomy. The report adopts a three-pronged approach to gather information: interviews of representatives of government, industry, and trade associations involved in the bio-based products; data collection from government agencies and published literature on the bio-based products industry; and economic modelling. Despite being intended as a platform for understanding and tracking the progress of the bioeconomy in the United States, the USDA 2016 report does not provide a complete picture of the bioeconomy, as it does not report on the bioenergy sector, which is included in the U.S. strategy. Instead, it only focuses on seven major sectors chosen to represent the bio-based industry's contribution to the US economy (agriculture and forestry; biorefining; bio-based chemicals; enzymes; bioplastic bottles and packaging; forest products and textiles). In 2017, also the Department of Energy (DOE) provided some figures about the size of the bioeconomy [30], building up the Billion Ton Bioeconomy Vision, but without a systematic measurement approach. The DOE estimates are taken from a paper considering direct employment and revenues from biomass resources fed into a number of end-uses and products including heat and power generation, bio-based chemicals and products (including wood pellets), and biofuels and coproducts [45].

3.4. Limitations in data availability and statistical approaches

Most of the analysed countries currently measure the contribution of bioeconomy to their GDP and other economic variables only. This economic approach, however, has some limitations to reflect the contribution in the economic sphere, above all because no standard methodology has been established to enable international comparison of bioeconomy contribution to GDP. Additionally, as mentioned above, products and activities comprised within the bioeconomy greatly vary according to country's priorities and comparative advantages.

The most common classifiers of economic activity, trade and products at international-level (International Standard Industrial Classification (ISIC), North American Industry Classification System (NAICS), Classification of Economic Activities in the European Community (NACE), Nomenclature for External Trade (NET), and Classifier per Category (CPC)) are not compatible with the complexity of the bioeconomy [11,38] since they are not appropriate for the heterogeneous nature and variety of bio-based products. ISIC, NACE and NAICS group production units according to the similarity of their productive processes, technology, inputs and equipment. Their classification criteria make no distinction between bio or non-bio inputs [11]. Even the System of National Accounts (SNA 08) from the United Nations, which provides recommendations for measuring the national production, wellbeing and other economic issues in an internationally comparable way, does not allow to measure the bioeconomy [11]. Classifiers based on the traditional industrial activities are not compatible with the bio-based industry. This can lead to under or over-estimation of the size of the bioeconomy.

The high number of bio-based products and their heterogeneity make it very difficult to provide a full quantitative picture of the status and evolution of the bioeconomy [46]. Often, data on the bioeconomy are retrieved from surveys of the bio-based industry [11,27,47]. These surveys represent an important first step for a systematic approach to quantify the bioeconomy; however, they face difficulties in assembling the requested data and suffer from incomplete response rate [47]. These limitations are even more relevant in low and middle-income countries, where statistical systems are not well-developed. Under these circumstances, the surveys may not be updated and/or may include limited and biased samples (as shown for instance by the Argentinian and South Africa analyses, where the last company surveys were taken in 2003 [48]). Digitalization efforts as the ones undertaken in Malaysia to improve data collection can play an important role in the measurement and monitoring of bioeconomy.

4. Discussion

4.1 The need for defining the bioeconomy boundaries at national, regional and global levels

Due to the lack of a homogenous definition of bioeconomy and its sectors, a common ground which enables comparing the contribution of bioeconomy among countries is missing. Also at national level, the definition of the bioeconomy boundaries is sometimes unclear. For instance, in the case of the Netherlands, the estimated impacts of bioeconomy were different among the official studies analysed, due to the variety of methodologies and input data [17,20,21]. Also in the U.S., most of the sectors considered by the DOE to estimate the size of bioeconomy were excluded from the USDA 2016 report, leading to different estimates of the bioeconomy impacts in the country [29,30]. For this reason, the efforts of the U.S. Biomass R&D Board to coordinate programmes within and among departments and agencies of the federal government towards a single, harmonized bioeconomy vision should ideally produce a single comprehensive approach able to monitor and measure all the sectors included in the vision in a coherent way.

When the countries do not have a holistic bioeconomy strategy, they tend to adopt a fragmented approach by separately considering the different uses of biomass in each sector (e.g. agriculture, forestry, energy, transport). This approach to governing the bioeconomy leads to different policies for different uses of biomass, different incentives for investment and different regulations for the areas from which feedstocks are sourced [49]. In these countries, the efforts should aim at integrated approaches across different levels, sectors, landscapes and end-uses, in order to avoid boom and bust policies as it happened for first-generation biofuels in the EU and elsewhere.

Nevertheless, some regional efforts to harmonize the measurement of the bioeconomy's economic significance exist. For instance, since the launch of the European Commission (EC) strategy for the bioeconomy in 2012, the EC Joint Research Centre (JRC) is monitoring jobs and turnover in the European Union bioeconomy for all the member states and sectors [50]. In order to enable achievement of the full potential of the bioeconomy, global guidelines on the measurement and regulation of the value chains could be beneficial [8]. FAO has been already coordinating the global

efforts towards the development of international Bioeconomy Sustainability Guidelines. These could be used by the countries to measure sustainability aspects of their bioeconomy strategy and monitor the achievement of economic, social and environmental targets and priorities.

4.2 Bioeconomy as a means to achieve Sustainable Development Goals

The bioeconomy has already been adopted by a significant number of countries as a new vision of development to decouple the economy from the fossil fuels dependence, and as a valid path towards the achievement of the Sustainable Development Goals (SDGs) and the commitments under the Paris Climate Agreement. For instance, the efficient and sustainable natural resource management is directly tied to at least 12 of the 17 SDGs and can cut GHG emissions by 60 percent by 2050 [51]. In addition, for lower income countries, better management of natural resources is often a key component of poverty eradication, climate change mitigation and resilient economic growth [52].

In low and middle-income countries with available biomass resources and/or well-developed primary sectors, a sustainable bioeconomy could unlock new opportunities for economic development and industrialization, and support economic and social objectives, such as reducing unemployment and expanding access to energy. For instance, in Argentina (and similarly in other Latin American countries with high feedstock availability), the increase in the value added to agricultural production can create employment and improve the competitiveness of export-oriented sectors. The agriculture sector of the region has the potential to generate productivity gains, which could result in significant improvements in countries' inclusion in international trade [11]. Improvement in agricultural productivity can also play an important role in building resilience while increasing yields for farmers [36]. Countries with low labour productivity level in the bioeconomy sectors but abundant primary production and a sound manufacturing base could add value through bio-based methods of production [38].

The agriculture sector is also a key component of the bioeconomy strategy for middle-income countries such as Malaysia and South Africa. In Malaysia, the performance of the palm oil sector seems to somewhat determine the overall direction of Malaysian bioeconomy development [37]. In South Africa, enabling job creation through the expansion and intensification of sustainable agricultural production and processing is part of the three strategic objectives of the bioeconomy.

In the U.S., with both high feedstock potential and advanced industries, the bioeconomy is based both on the expansion of biomass and on 'bio-inventions' [25,53]. However, a bioeconomy vision based on the expansion of biomass can face challenges, such as the reliable availability of raw materials due to the increased climate and severe weather impacts, water availability, and stability of the markets [44].

In contrast, some high-income countries such as the Netherlands have excluded the agriculture and food sector from their bio-based economy strategy. The main reasons for this is the limited domestic supply of ecologically sustainable biomass, which concerns several other EU countries as well. Estimates suggest that, for the EU, the sustainable biomass supply will be enough to meet about 10% to 20% of the final energy and feedstock consumption in 2030 [40]. Considering that land use is the most critical issue in sustainable biomass production, countries with limited land availability face relevant constraints. In countries with limited biomass availability, such as some Western European countries, the bioeconomy strategies focus more on biochemistry and bio-pharmacy benefiting from long-standing experience and R&D investments [50]. In countries focusing on high value-added bioeconomy sectors, bioeconomy can generate higher turnover compared to the employment generated, whereas the less value added sectors of the bioeconomy (mainly primary biomass production in agriculture, forestry and fisheries) typically generate more employment.

Technical innovation and new business models associated with the bioeconomy should potentially aim at decoupling economic growth from resource use also in countries with available resources [52]. A sustainable bioeconomy would not foster depletion of resources, degradation of the environment, loss of biodiversity and social injustice. As Germany recognizes in its bioeconomy strategy, the structural transition towards a bio-based economy can be successful only if it secures

the supply of food, it protects the environment, the climate and biodiversity, and it supports the development-policy objectives in developing countries and emerging economies [13].

4.3 Linking goals and measurement frameworks

If a bioeconomy strategy aims to contribute to sustainable development and to environmental and social objectives (e.g. employment, food security, energy security, mitigation and adaptation to climate change [10]), these should be clearly included in the strategy objectives and should be measurable (by means of quantitative, qualitative or as aggregate indicators). Environmental and sustainability components in bioeconomy development approaches should be closely connected with supply and production of bio-resources, as well as with consumption patterns. In fact, the core of transformational strategies is not limited to the technological aspects, but includes behaviour change and institutional innovations for enabling settings and long-term incentives, both at the company and of international policy levels [39].

This study shows that a means to monitor progress in reaching the targets set in the bioeconomy policies and strategies is lacking in many countries, and the difficulty of measuring it can be a consequence of the lack of a clear definition of the bioeconomy concept and of concrete and measurable objectives. In fact, strategies often show non-measurable objectives and qualitative targets. In the case of South Africa and United States, for example, the suggested output indicators of critical factors to monitor bioeconomy strategy [23] and the bio-based economy indicators and composite indicators [27] have not been measured in the practice yet due to the lack of sufficient data.

Most countries monitor bioeconomy progress just with economic values and shares of GDP, while other aspects of sustainability and resource availability are addressed only to a limited extent [54]. The GDP is a parameter which certainly gives information on the bioeconomy contribution to the economy; however, it is not ideal due to the inadequacy of the standard industrial classification systems to systematically monitor bio-based production; the lack of systematic data and the often scattered information collected at national level. In addition, the GDP is being increasingly criticized as an inappropriate indicator to measure sustainable development since it includes activities considered detrimental to humans and the environment, and does not take into consideration social aspects that define human well-being, nor the environmental aspects (which are all important information to assess the real contribution to the overall economy). Moreover, the GDP does not include transfer payments, such as subsidies for fossil fuels [55].

In addition to GDP, other economic indicators often used to measure bioeconomy are: turnover (revenue from sales), employment, resource use (crops, wood, waste, land, capital, etc.), primary production of biomass in the country (agriculture, forestry, residues, fisheries, waste), import of biomass to the country, global land use for biomass based consumption in the country, production of bio-based products, price of biomass and bio-based products, consumption of bioeconomy products and trade flows [18,27,35,50]. Further indicators focus on the drivers of innovation, such as investments and spending in R&D or intellectual property. However, it can be difficult to capture the impacts of a new innovation due to a time lag between investments and outcomes. These types of indicators could be used to compare country performance in the development of a bioeconomy (e.g. which countries have a bioeconomy strategy or have dedicated R&D funds).

Some countries currently measure only the effect of bio-based *products* on the GDP, although bioeconomy related *services* could be included in the measurement of the bioeconomy. For instance, Finland includes nature tourism, hunting and fishing as bioeconomy services in its bioeconomy strategy [56]. Also the Malaysian BCI currently measures primarily revenues and economic flows, but it could be improved to take bio-services into account as well as broader socio-economic or environmental aspects. For instance, the BCI could incorporate measures of poverty reduction or income inequality in the bioeconomy industry, it could account for CO_2 emissions, or level of local biodiversity [43].

Nevertheless, some efforts to develop measurable social and environmental indicators to monitor the bioeconomy exist. For instance, Italy has developed a set of sustainability indicators with measurable impacts on food security, natural resources sustainability, dependence on non-renewable

resources, climate change, in addition to economic growth [57]. These indicators on sustainability dimension are based on the results of Systems Analysis Tools Framework for the EU Bio-Based Economy Strategy (Sat-BBE) consortium [35]. In order to measure the environmental impact of the bioeconomy, the EC JRC has developed and integrated modelling framework (IMF) to implement the consequential life cycle assessment (C-LCA). This framework identifies the consequences that a decision in the foreground system has for other processes and systems of the economy, both in the analysed background system and on other systems outside the boundaries, and allows policy impact assessment once it is fully implemented [47]. However, data gaps still need to be filled and concepts and methodology, including the IMF for the environmental impact assessment, need to be further developed and implemented.

Other environmental assessment and environmental management techniques include carbon footprinting, eco-audit, environmental and social impact assessment, and strategic environmental assessment [58]. An ongoing project, *MontBioEco* (from the Natural Resources Institute Finland (Luke), the Standing Committee on Agricultural Research (SCAR) Bioeconomy Strategic Working group (BSW), and CASA Ministry of Agriculture and Forestry Finland (MMM)) is developing a synthesis on bioeconomy monitoring systems in the EU Member States, including indicators and sub-indicators. The analysis has currently developed 22 indicators and 146 sub-indicators, around five main objectives: creating jobs and maintaining competitiveness; reducing dependence on non-renewable resources; mitigating and adapting to climate change; ensuring food security and managing natural resources sustainably [59]. This assessment includes the development of measurable indicators and sub-indicators that go beyond economic monitoring.

In countries with an existing bioenergy or biofuels strategy, efforts towards monitoring the sustainability of bioeconomy can be linked with the previous efforts on biofuels, biomass and bioenergy. Moreover, several standard, certification and labelling initiatives already set some indications both on the 'quality' of the bio-products and on their sustainability. For instance, the USDA has developed a *Certified Biobased Product* label which certifies the carbon content of a number of bio-products. Many existing bio-product certifications and standards give indications for monitoring environmental and social sustainability.

A further step in monitoring bioeconomy should ideally include the measurement of taxation and regulatory support. For instance, the Dutch RVO estimates also the investment in BBE R&D through tax credits and fiscal exemptions [20]..

Other national studies are analysing existing policy to assess how public finance, regulations and capacity building can enable growth of the bioeconomy (see for instance [60] for Thailand).

Bioeconomy is also an opportunity for young people and next generations, and it is often linked to improving science, technology, engineering, and mathematics (STEM) education and training programmes to meet the workforce needs. For instance, these aspects come as a key priority in the US bioeconomy strategy and the Finnish bioeconomy strategy, for which developing the bioeconomy competence base by upgrading education, training and research is a key objective [56]. Also the South African bioeconomy strategy and the indicators suggested in the strategy, being driven by the Department of Science and Technology, have an 'innovation' bias. In fact, most indicators in the strategy are related to science, technology and innovation, as they are derived from the measurement of a knowledge-based economy or biotechnology innovation policies [23].

Finally, in Argentina, Malaysia and South Africa, one of the bioeconomy objectives is to strengthen infrastructure to support economic growth and increase access to national and international market [10,15,23]. Therefore, this aspect should ideally be included in a pathway towards a sustainable bioeconomy monitoring including socio-economic and environmental impacts. Other aspects, such as the inclusion of gender (not mentioned as priority in any of the strategy analysed), may be included in the measurement framework, in order to reflect country's priorities and strategy.

5. Conclusions

This study underlines the lack of a homogenous definition of bioeconomy across the countries analysed, which does not allow any straightforward comparison of the relevance of bioeconomy in the different economies.

The sectors comprised mostly reflect priorities identified by the country and comparative advantages linked for instance to availability of natural resources, traditional industries, labour productivity and past investments in R&D. For instance, the agri-food sector is identified as a priority for Argentina, Malaysia and South Africa; while the Netherlands and the Unites States focus more on non-food sectors.

Most countries measure bioeconomy progress just with economic values and shares of GDP. On top of the lack of international consensus on which products and activities are comprised within the bioeconomy, the GDP approach has several limitations due to the inadequacy of the standard industrial classification systems to systematically monitor bio-based production; the lack of systematic data and the often scattered information collected at national level.

Usually, bioeconomy strategies also consider intangible aspects, such as institutional set up, policies, governance, regulations, incentives and financial instruments, which create an enabling environment for the bioeconomy, as well as social and environmental issues. Several countries emphasize the role that bioeconomy plays in their development strategy, which is an important aspect to reflect in their measurement efforts. This could allow monitoring, for instance, progress in meeting the SDGs or environmental targets. In fact, important synergies between countries commitments towards the measurement of SDGs and bioeconomy can be leveraged.

In order to facilitate the measurement and monitoring of bioeconomy at a national level, the governments could enhance and coordinate communication between different domestic agencies and entities and establish protocols for sharing data; formalize bio-based industry measurement standards; develop a comprehensive survey for bio-based industry and commodity usage; and review and revise industry classification systems. Ongoing efforts aim to harmonize the definition and measurement of bioeconomy, at least across macro-regions, such as the EU. These efforts will allow to have structured and comparable measurement and monitoring of the trends in bioeconomy. These efforts should go hand-in-hand with the development of relevant and comprehensive guidelines on how to measure the sustainability of the bioeconomy, possibly agreed at an international level. These sets of indicators should also consider social and environmental issues.

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