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Measuring the Chinese bioeconomy: a hypothetical extraction method with input–output tables

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Abstract

The bioeconomy has received significant policy attention globally, particularly in the United States and the European Union, where extensive studies have evaluated its economic importance and strategic potential. In contrast, Asia's bioeconomy, despite its substantial contributions to global biomass production and biotechnology, remains comparatively underexplored. This paper presents a study on the Chines bioeconomy value added covering the period 1995–2018, using OECD input–output statistics and the hypothetical extraction method (HEM). Our findings reveal that the Chinese bioeconomy contributes 16% to the entire economy in 2018. Furthermore, we compare the bioeconomy value added and growth rates of ten countries during the same period. The two non-OECD countries, China and India, exhibit higher percentages of bioeconomy value added, both between 15 and 19%, than the other eight OECD countries, where the percentages remain below 10%. Our results indicate that, while the total value added and bioeconomy value added fluctuate for all ten countries, the two curves follow similar trends for all countries except the United States and China. Additionally, we compare the HEM results with other methodologies and observe that the HEM and the input-based method yield similar outcomes for China, while both are considerably lower than the up- and downstream approach. This has implications for assessing the contribution of the bioeconomy for sustainable development.

Keywords Bioeconomy · China · Hypothetical extraction · Input–output · Value added

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1 Introduction

Developing the bioeconomy is widely recognized as a strategic approach to addressing global challenges, including food security, energy crisis, resource scarcity, healthcare, environmental sustainability, and climate change (Mesa et al., 2024; M'barek & Wesseler, 2023; Issa et al., 2019; Zilberman et al., 2018). By fostering innovation and efficiency in resource use, the bioeconomy plays an important role in advancing sustainable development and enhancing economic, social, and environmental well-being (Calicioglu & Bogdanski, 2021; Razminien et al., 2021; Wesseler & Zhu, 2024). Certain bioeconomy practices and applications have made remarkable strides in recent years, demonstrating significant advancements in areas such as sustainable agriculture, renewable energy, and biotechnological innovations (Maroušek et al., 2015). Over recent decades, it has emerged as a focal point for scientists, policymakers, and stakeholders, reflecting its growing significance in shaping a sustainable future.

Many countries, regions, or organizations have issued policies, plans, or guidelines to promote the development of the bioeconomy (Dietz et al., 2018; Proestou et al., 2024). OECD published *The Bioeconomy to 2030: Designing a Policy Agenda*, providing a comprehensive, policy-focused, forward-looking study and examining the implications of future bioeconomy advancements in primary production, health, and industry (OECD, 2009). The United States (US) presented the background, impacts and federal strategy of the bioeconomy in the *National Bioeconomy Blueprint* (The White House, 2012). The European Union (EU) has supported developing bioeconomy to achieve a more sustainable development since early 2000s (Sharma & Malaviya, 2023; Woźniak et al., 2021), and adopted the strategy *Innovating for sustainable growth: a bioeconomy for Europe*, proposing its strategy and action plan to foster a more innovative, resource efficient and competitive society (European Commission, 2012). In 2018, the EU bioeconomy strategy got updated to strengthen the connections of economy, society and environment (Bell et al., 2018; de Besi & McCormick, 2015). Also, many EU member states declared related policies (Bosman & Rotmans, 2016; Falcone et al., 2020; Lühmann & Vogelpohl, 2023).Some emerging countries, like China, Brazil, South Africa, India, Argentina, and Malaysia, also declared related policies to support the bioeconomy (Arujanan & Singaram, 2018; Bracco et al., 2018; Lee & Hamelin, 2023).

The bioeconomy has made important contributions to economic growth. The US biobased products industries employ 4.65 million people and create \$459 billion and the biotech sector revenue has increased by more than 10% each year over the past decade (Carlson, 2016). The EU bioeconomy creates €615 billion of value added, €2.2 trillion of turnover, and employs 18 million persons (Ronzon et al., 2017). German bioeconomy contributes 6% to the total economy in 2010 and increases by 22% from 2002 to 2010 (BMEL, 2016). Dutch Bioeconomy is estimated up to €64,308.43 million value added, accounting for 10.4% of the total economic growth in 2015 (Cingiz et al., 2021). Canadian biobased economy in 2007 is valued at approximately \$78.3 million, about 6.4% of its total GDP (Pellerin & Taylor, 2008).

Although many economies have issued policies to support bioeconomy development, there is no unified definition and scope. From OECD, the bioeconomy encompasses biotechnological knowledge, renewable biomass, and the integration of these elements across various applications (OECD, 2009). European Commission defines bioeconomy as resource-focused, including not only the primary sectors but also the up- and downstream sectors(European Commission, 2012), and expands the scope to ecosystem services and all economic sectors in 2018 (European Commission, 2018). Finnish definition covers all renewable natural resources (Kuosmanen et al., 2020; Ministry of Economic Affairs and Employment et al., 2014). There are various understandings about which sectors should be included in bioeconomy based on a common approach of estimating the size through sectoral data (Bracco et al., 2018; Lier et al., 2018), but most definitions share similarities and focus on resources and agriculture (Frisvold et al., 2021; Guo & Song, 2019; Wesseler & von Braun, 2017).

The Chinese government has also laid great emphasis on bioeconomy (bio-business, bio-based economy) and the Chinese bioeconomy has experienced remarkable growth. The central government listed genetic engineering research, which is an influential part of the development of bioindustries such as biomedicine and vaccines, in the national plan in the 1980s and allocated funds to advance genetic engineering (Wang et al., 2018). Since then, the policies about bioeconomy, bio-business, and bio-based products have been getting more attention from the government and the public. In 2022, China issued its first dedicated bioeconomy plan *Bioeconomy Development Plan in the 14th Five Years* (2021–2025), prompting the development of biomedicine, bio-agriculture, biomass substitution, and biosafety. The biological industry in China increased by 22.9% annually between 2006 and 2010. By 2011, the total output value had reached about $310 billion (The State Council of the People's Republic of China, 2012).

The ecological impact of the Chinese bioeconomy, as reflected in economic terms, is substantial, particularly in its contributions to resource efficiency, carbon mitigation, and environmental sustainability. For instance, China's bioeconomy sectors, including biomass energy, biotech agriculture, and bio-based materials, play a key role in reducing greenhouse gas emissions and decreasing dependence on fossil fuels, translating into cost savings from avoided environmental damages and carbon offsets. Additionally, sustainable practices in biotechnology and agriculture enhance soil health, reduce water usage, and lower the ecological footprint, contributing to long-term savings in natural resource management. These impacts align with estimates showing billions of dollars saved annually through cleaner energy solutions and improved agricultural productivity, further reinforcing the link between ecological benefits and economic gains.

While much has been done in other countries, little scientific literature on quantitative analysis could be acquired about the Chinese bioeconomy. Both scientists and policymakers are not clear about its size and position in the world. The potential contribution of the Chinese bioeconomy to economic growth and sustainable development has garnered significant interest.

The research question addressed in this paper is: How much does the Chinese bioeconomy contribute to economic value added, and how does it compare to other countries? To measure and compare this contribution, we employed the Hypothetical Extraction Method (HEM), alongside two additional approaches: an input-based method and an upstream–downstream method. These methodologies were applied using the OECD input–output dataset. The novelty of this study lies in two key aspects. First, it provides the first comprehensive measurement of the size of China's bioeconomy. Second, it introduces the innovative use of HEM in this context, offering new insights into the economic influence of the bioeconomy. The rest of the paper is structured as follows: In Sect. 2, we review the methodologies about measuring bioeconomy, with a particular focus on HEM. Section 3 introduces HEM in detail and explains its application to the measurement of the bioeconomy. Section 4 outlines the data sources and presents the results derived from HEM. Section 5 compares these results with findings from the input-based and upstream–downstream methods. Section 6 concludes with a summary of findings, along with conclusions on the implications and limitations of this research.

2 A literature review

2.1 Review methodologies measuring the bioeconomy

To determine the bioeconomy size, a commonly employed method involves aggregating all sectors that constitute the bioeconomy using sectoral data. Table 1 gives an introduction of the literature measuring the bioeconomy. The initial stage of the analysis involves identifying and defining the sectors that fall within the bioeconomy category. Once these sectors are identified, various methods can be employed to measure the proportions of the bioeconomy within each sector. These methods aim to quantify the bioeconomy's share within each sector, providing a clearer understanding of the overall size and contribution of the bioeconomy.

Output-based methods estimate sectoral bioeconomy shares through sectoral outputs, which could be derived from statistics, reports, surveys or experts. Nova-Institute and Joint Research Centre (JRC) have proposed an output-based methodology in 2012 and updated it in 2017 (Ronzon & M'Barek, 2018; Ronzon et al., 2017). They calculated the bioeconomy value added, turnover, and employment of 28 EU member states from industrial and market experts' opinions. Their results show that 18 million people are employed by the EU-28 bioeconomy in 2015, and it generates €2.3 trillion in revenue or €620 million in value added. The Thünen Institute adopts an output-based approach, focusing on producing biomass, bio-based materials and end-use products (Iost et al., 2019), and estimate that the German bioeconomy creates 3.7–4 million jobs, €116–135 billion value added and €451–520 billion turnover in 2014. Ronzon et al. (2017) measure the sectoral bioeconomy through experts' estimations about the proportions of sectoral bio-based products and find that in 2014 about 18.6 million people are engaged in the EU bioeconomy, with about €2.2 trillion turnover annually. Some research results (Capasso, 2021; Ronzon et al., 2020, a) and statistics data are combined to determine that the EU bioeconomy services account for between 5.0 and 8.6% of GDPs, and 10.2–16.9% of employment from 2015 to 2017 (Ronzon et al., 2022b).

Input-based approaches measure the sectoral bioeconomy proportion through sectoral biobased inputs, and the assumption is that one unit of biobased input generates a unit of bioeconomy output. The biobased inputs are inputs from primary sectors, biomass, or particular sectors identified by researchers (Ronzon et al., 2022b). Heijman (2016) proposes a two-sector input-based method to measure Dutch bioeconomy and finds its value added accounts for 6.7–7.2% of GDP from 2008 to 2012. Kuosmanen et al. (2020) compare this method and the Nova-Institute method and find that the results of Heijman's method are slightly lower when measuring the Finnish bioeconomy in 2015. They use a classic three-sector model by specifying primary, secondary and tertiary industries, using sectoral bio-based inputs to estimate the sectoral bioeconomy shares.

There is also literature considering both inputs and outputs. Cingiz et al. (2021) propose an up- and downstream method by extending Heijman's method to include not only the downstream but also the upstream linkages, and get the results of 28 EU Member States from 2005 to 2015. As a result, the bioeconomy value added is larger than Heijman's results, with the Dutch bioeconomy contributes to 8.37% of GDP which is larger

Table 1 Literature review of methods for measuring bioeconomy[1]

References	Region	Period	Measurement	Method	Sectors
Pellerin and Taylor (2008)	Canada	2007	Value Added ($78.3 billion, 6.4%)	A three-phase approach	NAICS[2] codes: 62, 111, 212233, 3254, 32519, 3251, 3121, 31151
Vandermeulen et al. (2011)	Flanders, Belgium	2010	Value Added (1.8%)	Industry surveys	Biobased energy and biobased products
Golden et al. (2015)	United States	2013	Value Added (2.2%)	IMPLAN software	Seven major sectors
Carlson (2016)	United States	2012	Turnover (around 2%)	Data from financial, reports, and surveys	Biologics (biotech drugs), GM crops and industrial biotech
Efken et al. (2016)	Germany	2007	Value Added (7.6%)	Input–output tables	Primary sectors and all downstream sectors, but excluding upstream industries
Heijman (2016)	Netherlands	2008–2012	Value Added (6.6–7.2%)	Input–output tables	All sectors
Ronzon et al. (2017)	EU28	2014	Employment (18.6 million), Value Added (€2.2 trillion)	Input–output tables	NACE[3] codes: A01-03, C10-17, C20-22, C31, D3511
Iost et al. (2019)	Germany	2014	3.7–4 million jobs, €116–135 billion value added and €451–520 billion turnover	An output-based method with data from statistics and surveys	NACE codes: A, C, D, F, I, M
Loizou et al. (2019)	Poland	2010	Bioeconomy output, employment and income of each sector	National input–output tables	NACE codes: A01-03, C10-17, C20-22, C31, D3511
Ronzon et al. (2020)	EU28	2008–2017	Value Added: food, beverages and tobacco (37%), agriculture (30%)	Data from EUROSTAT and biobased shares from nova Institute	NACE codes: A01-03, C10-17, C20-22, C31, D3511
Cingiz et al. (2021)	EU28	2005–2015	Value Added (most member states 40–50%)	Up- and downstream effects	NACE codes: A01-03, C10-C22, C31, D35, E36, E38-39, G46-47, H, I55-56, M7211, R9104
Ronzon et al. (2022a)	EU27	2015–2017	Bioeconomy Services: Value Added (5.0–8.6%); Employment (10.2–16.9%)	Data from literature or statistics	NACE codes: G to T

Table 1 (continued)

References	Region	Period	Measurement	Method	Sectors
Lazorcakova et al. (2022)	Visegrad countries	2015	economic output (13%), value added (10%), employment (15%), GHG emissions (20%)	Input–output analysis	CPA[4] 01, 02, 03, 10, 11,,12, 14, 16, 17, 13, 14, 20, 21, 22, 31, 35

[1]Retrieved from and modified based on the table in Cingiz et al

[2]NAICS (The North American Industry Classification System) serves as the standardized system used by federal statistical agencies to categorize business establishments. See https://www.census.gov/naics/

[3]NACE (Nomenclature of Economic Activities) is the European standard for classifying economic activities. NACE groups organizations according to their business activities. See https://nacev2.com/en

4The Statistical classification of products by activity, abbreviated as CPA, is the classification of products (goods as well as services) at the level of the European Union (EU). See https://ec.europa.eu/eurostat/web/cpa/cpa-2008 than Heijman's result of 7.2%. Kuosmanen et al. (2020) introduce an input–output-based method that utilized a weighted average of the input- and output-based proportions. Using this approach, they estimated the EU-28 bioeconomy value added in 2015 is at €1460.6 billion, accounting for 11% of the total economy.

In addition to the previously mentioned methods, researchers have proposed alternative methodologies from different perspectives. Vandermeulen et al. (2011) present a framework where some key points like conceptualization, disaggregation, information and valuation, may vary in different situations, and they perform a case study focusing on biobased energy and products in Flanders, Belgium, and find that Flemish bioeconomy value added accounts for 1.8% of GDP. Golden et al. (2015) utilize the IMPLAN modelling software to analyze the flow of spending throughout the US economy and specifically examine the impact of biobased sectors on the economy. Their findings indicate that the value added by the US bioeconomy accounts for only 2.2% of GDP in 2013. Another estimation comes from Carlson (2016), who estimates the size of the biobased economy to be approximately 2% in 2012. This estimation is based on publicly available data concerning the total revenue generated by genetically modified organisms and the products derived from them. These studies demonstrate that various approaches and methodologies exist for assessing the size of the bioeconomy, each with its own unique perspective and considerations. The results obtained may differ depending on the specific context and the methods employed.

2.2 Review HEM

HEM was introduced by Paelince et al. (1965), and developed by many scholars to study the importance of an industry or set of industries to an economy (Cella, 1984; Groenewold et al., 1987; Heimler, 1991; Milana, 1985; Strassert, 1968). HEM utilizes input–output tables to hypothetically remove a specific sector from an economic system and evaluate its impact on the overall economy. The difference between the original output and the output after extraction quantifies the interdependence and contributions of the removed sector (Dietzenbacher & Lahr, 2013; Dietzenbacher et al., 2019; Hertwich et al., 2024).

A typical use is to evaluate the interdependence or importance of some sectors with input–output tables. Deng et al. (2018) adopt a generalized HEM to measure water trade in China and conclude that the linkages between agriculture and other industries affect both the imports and exports volume of China's virtual water. Song et al. (2006) adopt HEM to measure the quantitative interdependence of the construction sectors. They find that the connection between the real estate sector and the remaining sectors is increasing. Duarte et al (2002) build a modified HEM to measure water use in Spain and confirm the importance of Agriculture, Food and Other Services in water consumption. Dietzenbacher and van der Linden (1997) describe the interdependencies in the production structure of European countries focusing on both the sectoral and the spatial dimensions.

A more widely used field is energy, such as GHG emissions. Using HEM, Rasul and Hertwich (2023) and Hertwich (2021) quantifies the carbon foodprint of primal metals and materials production, identifying the importance of different linkages. Wang et al. (2013), Zhao et al. (2015), and Ali (2015) use HEM to evaluate the CO_2 emissions of different regions. In their studies, data from input–output tables and the HEM method are key factors affecting the results. Sajid et al. (2019) measure the carbon linkages of the Turkish economy with the HEM method from both the demand and supply sides including both backward and forward linkages. Zhao et al. (2015) integrate HEM with the multi-regional input–output model and investigate the industrial CO_2 emission linkages of China at the regional level. Wang et al. (2021)

analyze the inter-provincial sectoral embodied CO2 net transfer with the HEM method in China and identify the key CO2 emitter sectors, which are mostly located in northwest China.

In general, the methodologies of measuring the bioeconomy are still developing and evolving. Wesseler and von Braun (2017) review the framework, data, and methodologies, and point out that the methodologies are still in their infancy and face many challenges. HEM is a widely used approach of measuring the size of intersectoral and interregional linkages such as the economic connections between sectors. The purpose of this paper is to provide the method HEM by extracting input–output streams and get the results of the bioeconomy value added of China and some other countries. Also, we compare HEM with the input-based methodology and up- and downstream methodology. We hope this method could contribute to the inspiration of research methodologies.

3 Material and methods

In this part, we first introduce HEM and explain the method of using HEM with input–output tables. Then following the principle of HEM, we describe how it could be adopted to measure the size of the bioeconomy.

3.1 Method of HEM

To introduce HEM, firstly we will illustrate the notations used in a basic table. As the notations in Miller and Blair (2009), let z_{ij} denote the input from i to j, f_i denote the final demand of i including imports and exports, v_i denote the value added of i, x_i denote the output of i. All transactions are quantified in monetary terms, and all variables are members of the set of real numbers. The structure of an input–output table is shown in Table 2.

We have $Z = \left(z_{ij}\right) = \begin{pmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nn} \end{pmatrix}, f = \left(f_i\right) = \begin{pmatrix} f_1 \\ \vdots \\ f_n \end{pmatrix}, V = \left(v_i\right) = \begin{pmatrix} v_1 \\ \vdots \\ v_n \end{pmatrix}, X = \left(x_i\right) = \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix}.$

This table makes clear the inter dependencies between industries within an economy. Each column represents the monetary inputs of one sector to each sector, and each row represents the monetary outputs of one sector to each sector. And the equations are:

$$X = Ze + f \tag{1}$$

$$X = Z\prime e + V \tag{2}$$

Table 2 The input–output table basic structure

	Sector 1	…	Sector n	Final demand	Total
Sector 1	z_{11}		z_{1n}	f_1	x_1
…	…	…	…	…	…
Sector n	z_{n1}	…	z_{nn}	f_n	x_n
Value added	v_1	…	v_n		
Total	x_1	…	x_n		

where $e = \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix}$, $Z\prime$ is the transpose of Z.

Let $A = \left(a_{ij}\right) = \begin{pmatrix} z_{11}/x_1 & \cdots & z_{1n}/x_n \\ \vdots & z_{ij}/x_j & \vdots \\ z_{1n}/x_1 & \cdots & z_{nn}/x_n \end{pmatrix}$ denote the Leontief direct input coefficient matrix, I denote the identity matrix, then the Leontief input inverse matrix is $L = (I - A)^{-1}$, and $X = Lf$.

Now, we demonstrate how HEM is used based on the methodology of Miller and Blair (2009). To identify how important some sectors, such as the first k sectors, are, now we partition A with the first k sectors in the upper left (square) submatrix. That is, we partition A into four submatrices, A_{11} including the first k rows and the first k columns of A, A_{12} including the first k rows and all columns except the first k columns of A, A_{21} including all rows except the first k rows and the first k columns of A, and A_{22} including the rest.

$$A = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix}$$

Assuming the first k sectors are extracted, we have

$$A_{11} = A_{12} = A_{21} = 0$$

It means removing all forward, backward, and internal relation. The original amount will be satisfied by imports. Then the new direct input coefficient matrix is $\overline{A} = \begin{pmatrix} 0 & 0 \\ 0 & A_{22} \end{pmatrix}$, new Leontief inverse matrix is $\overline{L} = \left(I - \overline{A}\right)^{-1}$; new output matrix is $\overline{X} = \overline{L}f$; new value added is $\overline{V}$.

The difference between original outputs and after-extraction outputs is the output contribution of the first k sectors. We get this result as follows:

$$\Delta\overline{X} = e\prime\left(X - \overline{X}\right) = e\prime\left(L - \overline{L}\right)f \tag{3}$$

The output could be translated into other variables like value added, income, employment or pollution with related coefficient matrix (Miller & Blair, 2009), and an example is that Kecek et al. (2019) calculate the value added and employment of ICT sectors. So to translate output into value added, we just multiply value added coefficients $\left(\frac{V}{X}\right)'$ by Eq. (3), and we could derive the value added $\Delta\overline{V}$ of the first k sectors in Eq. (4).

$$\Delta\overline{V} = \left(\frac{V}{X}\right)'\left(X - \overline{X}\right) = \left(\frac{V}{X}\right)'\left(L - \overline{L}\right)f \tag{4}$$

$\left(\frac{V}{X}\right)'$ is the value added coefficient matrix.

3.2 HEM to measure the bioeconomy

To measure the bioeconomy, HEM does not focus on the total inputs or outputs of each sector, but on the transactions between sectors. That is, we hypothetically extract the blocks of the inputs between sectors which are related to bioeconomy and calculate the difference between before and after extractions.

To analyze which block leads to bioeconomy, we classify all industries into two categories, fully bioeconomy sectors (F sectors) and partly bioeconomy sectors (P sectors), based on Kardung et al. (2021). The basic principle is (1) for F sectors, we think any transaction from any F sectors to F sectors (including itself) lead to bioeconomy. (2) for P sectors, we calculate the downstream effect, the blocks from F to P sectors, and the upstream effect, the blocks from P to F sectors. We do not include the blocks from P to P sectors.

For example, assuming industries 1, 3 and 5 are F Sectors, the rest are P Sectors. When extracting the blocks from F to F sectors, F to P sectors and P to F sectors in A, we could get

$$\overline{A} = \left(\overline{a_{ij}}\right) = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & a_{22} & 0 & a_{24} & 0 & a_{26} & \cdots & a_{2n} \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & a_{42} & 0 & a_{44} & 0 & a_{46} & \cdots & a_{4n} \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & a_{62} & 0 & a_{64} & 0 & a_{66} & \cdots & a_{6n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & a_{n2} & 0 & a_{n4} & 0 & a_{n6} & \cdots & a_{nn} \end{pmatrix}$$

We could calculate the bioeconomy through the difference between before and after extractions with equations in Table 3. And Fig. 1 gives an graphical illustration of the method application.

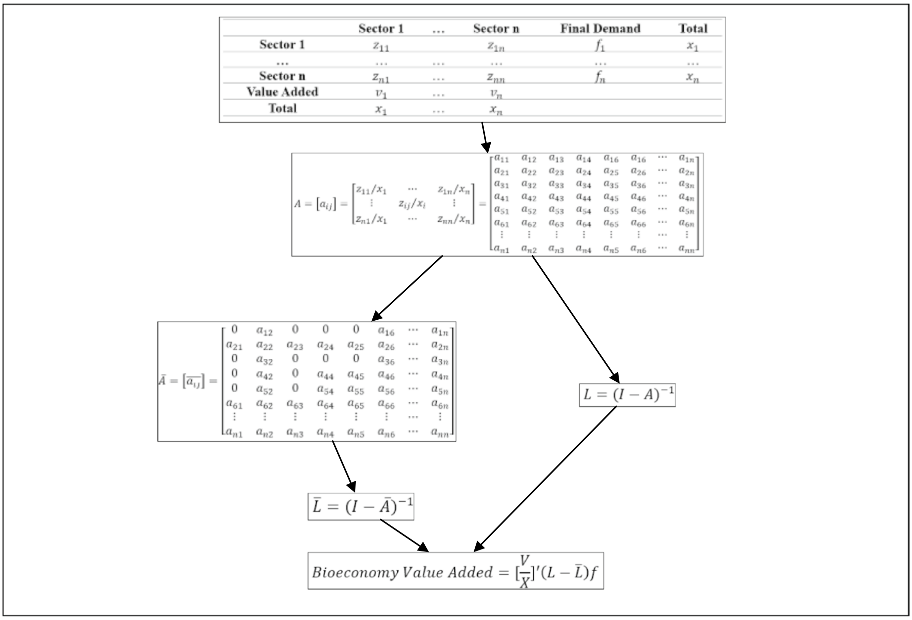

Fig. 1 A graphical illustration of the method

Table 3 Calculating bioeconomy with HEM based on Input–Output Table

	Original	After-Extraction
Coefficient	A	$\overline{A}$
Inverse	$L = (I - A)^{-1}$	$\overline{L} = \left(I - \overline{A}\right)^{-1}$
Output	X	$\overline{X} = \overline{L}f$
Bioeconomy Output	$e\prime\left(L - \overline{L}\right)f$	
Bioeconomy value added*	$\left(\frac{V}{X}\right)'\left(L - \overline{L}\right)f$	

*The equation to calculate the bioeconomy value added is Eq. (4)

4 Data and results

4.1 The size of Chinese bioeconomy

The data of input–output tables are taken from OECD statistics, with a time span between 1995 and 2018. The data of inflation are from World Bank GDP deflator statistics, and we let 1995 be the base year. We follow the classification of fully bioeconomy industries of Kardung et al. (2021) and relate it to OECD input–output tables following Cingiz et al. (2021) and think that all other industries are partly bioeconomy industries. So there are 5 F sectors and 40 P sectors in total (see Appendix). We could get the Chinese bioeconomy value added by HEM and the total value added by summation of each sector in Table 4.

Figure 2 demonstrates the bioeconomy value added and shares of China from 1995 to 2018. We can see a rapid increase in the bioeconomy value added. It keeps increasing from 1995 and reaches a peak in 2015, then begins to decrease in 2016, and goes up again from 2016 to 2018. The bioeconomy value added in 2018 is 7.84 times that in 1995, but the shares keep fluctuating in the range of 15% to 19% and do not see an obvious increase or decrease in general. In 2018, the bioeconomy value added reaches its maximum, but the percentage arrives at a new low point.

Figure 3 exhibits the value added growth rates of the bioeconomy and the total economy. Both growth rates keep fluctuating, and arrive at minimum values in 2016, with the growth of the bioeconomy at -2.78% and the growth of the total economy at 0.69%. The former reaches its biggest in 2011 at 19%, while the latter reaches its highest in 2008 at 22%.

To measure the bioeconomy of only a specific sector with HEM, such as Agriculture, hunting, forestry (code D01T02 in OECD input–output tables), we remove its connections to all F sectors and P sectors and calculate the difference between before and after the removing, which we think is its bioeconomy value added. We get 583,123.4 in 2018, while its total value added is only 415,427.4. That is, using HEM, the bioeconomy is bigger than the total contribution for Agriculture, hunting, forestry, with the ratio being about 140%. Similarly, we get 160% for Fishery and aquaculture, 269% for Food products, beverages and tobacco, 312% for Wood and wood products, 253% for Paper products and printing. We do not think these results make sense.

Table 4 The total and bioeconomy value added, growth rates and the bioeconomy percentage of China from 1995 to 2018 (1,000,000 dollars)

Year	Bioeconomy		Total		Bioeconomy share (%)
	Value added	Growth (%)	Value added (%)	Growth	
1995	126,103	–	690,867	–	18.25
1996	139,529	10.65	754,989	9.28	18.48
1997	151,184	8.35	822,314	8.92	18.39
1998	157,667	4.29	884,830	7.60	17.82
1999	174,122	10.44	947,247	7.05	18.38
2000	193,273	11.00	1,021,368	7.82	18.92
2001	204,740	5.93	1,108,871	8.57	18.46
2002	212,695	3.89	1,200,308	8.25	17.72
2003	223,863	5.25	1,308,323	9.00	17.11
2004	262,961	17.47	1,444,271	10.39	18.21
2005	310,164	17.95	1,618,260	12.05	19.17
2006	343,159	10.64	1,881,254	16.25	18.24
2007	406,657	18.50	2,235,940	18.85	18.19
2008	484,167	19.06	2,727,084	21.97	17.75
2009	519,467	7.29	3,048,218	11.78	17.04
2010	565,499	8.86	3,404,386	11.68	16.61
2011	673,770	19.15	3,904,178	14.68	17.26
2012	750,829	11.44	4,272,668	9.44	17.57
2013	841,172	12.03	4,700,176	10.01	17.90
2014	915,776	8.87	5,101,572	8.54	17.95
2015	973,458	6.30	5,437,248	6.58	17.90
2016	946,374	-2.78	5,474,802	0.69	17.29
2017	957,906	1.22	5,774,135	5.47	16.59
2018	989,259	3.27	6,296,353	9.04	15.71

4.2 An international comparison of the results

OECD statistics provide harmonized data for many countries and regions. We perform HEM to countries with the 10 biggest GDPs in 2018 and get the results in Fig. 4, which include the United States (US), China, Japan, Germany, United Kingdom (UK), India, France, Italy, Canada and Korea (see detailed data in supplementary materials).

We find that although the US has the largest GDP throughout these years, the Chinese bioeconomy value added has been the largest since 2011, about 1.56 times that of the US in 2018. Japan has the third largest bioeconomy value added in 2018, and the German bioeconomy ranks fourth in total and first in Europe.

Figure 5 describes the shares of the bioeconomy value added for these ten countries. An apparent characteristic is that the shares stay relatively stable for almost all countries throughout these years. For two non-OECD countries, China and India, the shares are much higher than the other eight OECD countries. The former fluctuates between 15 and 19%, while the latter are all below 11%.

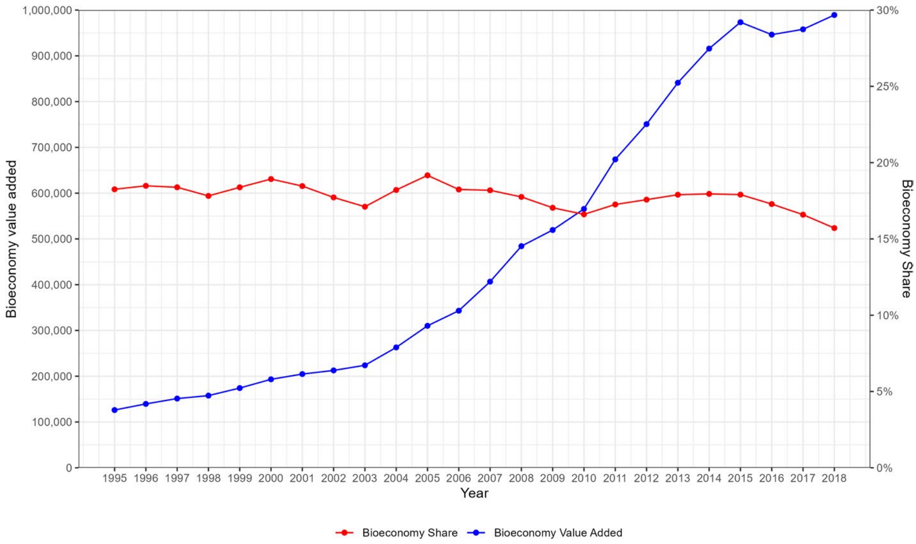

Fig. 2 The Chinese bioeconomy value added (1,000,000 dollars) and percentages

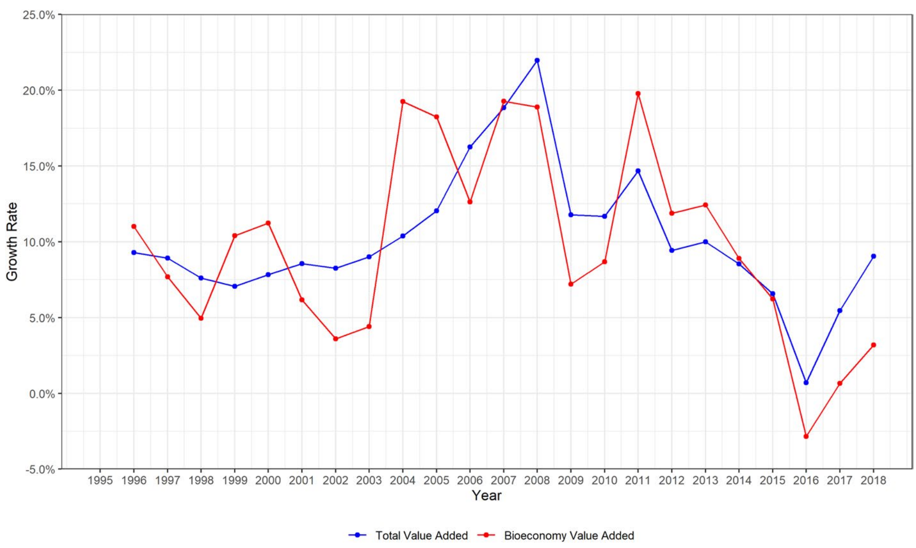

Fig. 3 The value added growth rates of the Chinese total economy and bioeconomy

Figure 6 depicts the value added growth rates of the total economy and the bioeconomy of the ten economies from 1995 to 2018. For the US, the growth rate of the total economy remains relatively stable while the growth rate of the bioeconomy has a larger fluctuation, with some years bigger than the total economy, and some years smaller. For China, as mentioned before, both growth rates keep fluctuating and do not see any similar trends. For the other eight countries, both curves fluctuate dramatically and almost synchronously.

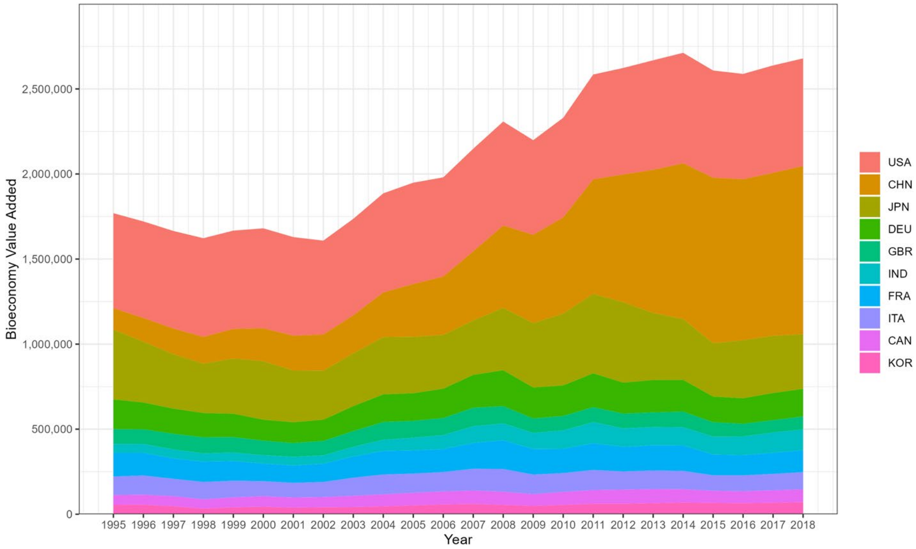

Fig. 4 The bioeconomy value added of the ten economies (1,000,000 dollars)

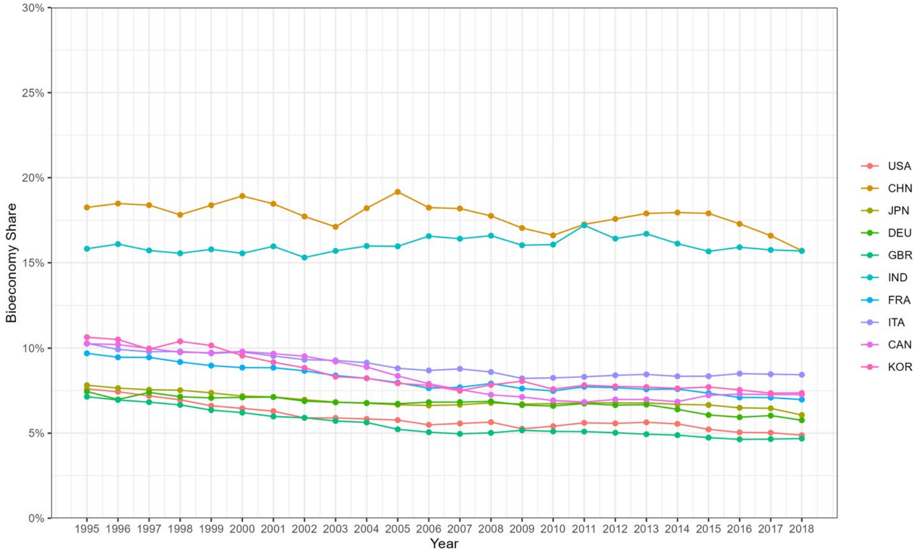

Fig. 5 The bioeconomy value added shares of the ten economies

4.3 A methodological comparison

Other methodologies including output-based approaches, input-based approaches, input–output-based approaches, and up- and downstream approaches are also widely used (Kuosmanen et al., 2020).

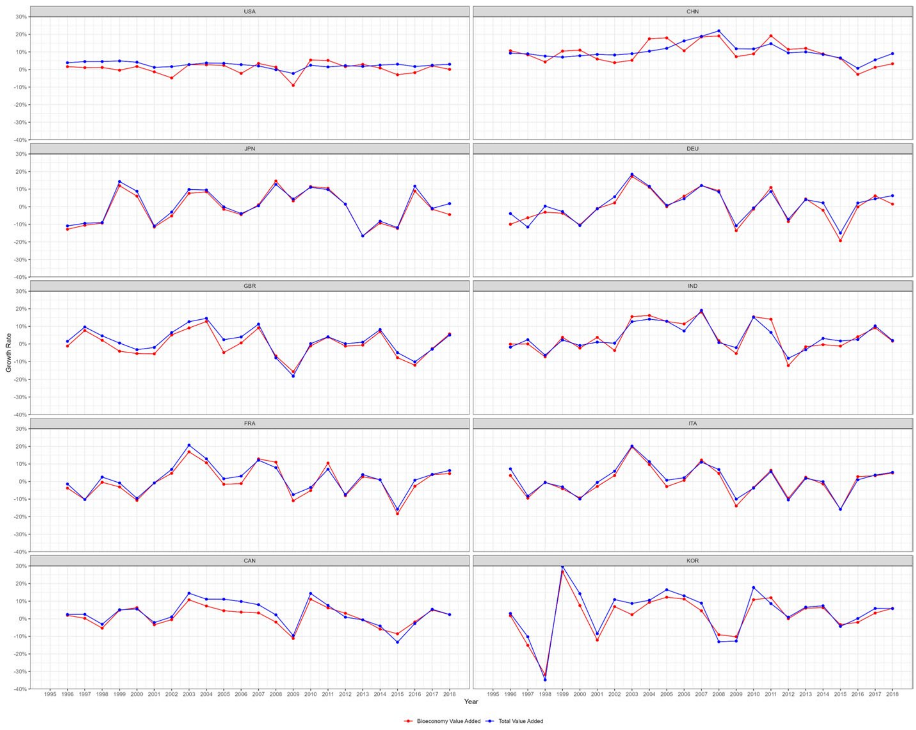

Fig. 6 The value added growth rates of the total economy and bioeconomy of the ten economies

Output-based approaches rely on estimations of the biobased output share for each sector. Iost et al. (2019) measure the German bioeconomy with data of Material and Goods received Enquiry, in which acquisition costs of all inputs are from surveys on 18,000 firms every four years. The biobased output shares of Ronzon et al. (2020) are derived from Eurostat structural business statistics and expert knowledge. Input–output-based approaches also use the biobased output share of each sector. For China, we did not find such statistics, nor did we do surveys on experts' estimations, so in this paper, the methodological comparison does not include output-based approaches and input–output-based approaches.

We compare HEM with input-based approaches and up- and downstream approaches. For input-based approaches, Kuosmanen et al. (2020) summarize different methods to estimate the biobased input shares. We will calculate the share for sector i following Kuosmanen et al. by

$$\gamma_i = \frac{\sum_{k=1}^{m} I_i^k + \sum_{l=m+1}^{o} \beta_l I_i^l + \beta_{M_i} M_i}{\sum_{j=1}^{n} I_i^j + M_i}$$

where $\beta_i = \frac{\sum_{k=1}^{m} I_i^k + \beta_{M_i} M_i}{\sum_{j=1}^{n} I_i^j + M_i}$, $k = 1, ..., m$ indicates fully bioeconomy sectors, $l = m + 1, ..., o$ indicates partly biobased sectors, I_i^j indicates the inputs from i to j, M_i indicates the imports of i, β_{M_i} indicates the share of biobased imports of i. Kuosmanen et al. consider that fully bioeconomy sectors include sectors C01–C03 and C10–C17, and partly bioeconomy sectors include sectors C22–C25. But for consistency of the comparison, we use the same bioeconomy classification with Cingiz et al. (2021), such that in fully bioeconomy sectors, we exclude C13–C15 and include C18 because the OECD input–output tables combine C17 and C18 as one sector, and partly bioeconomy sectors cover a wider range as we showed before. Please note that the fully bioeconomy sectors are not 100% included in the calculation as is shown in Sect. 4 of Kuosmanen et al. (2020) and their bioeconomy shares are also measured by γ_i.

For up- and downstream approaches, we follow Cingiz et al. with the equations below to calculate the downstream and upstream effects.

$$D_j^t = \frac{\sum_i I_{ij}^t}{\sum_k I_j^t} * V_j^t = \beta_j^t * V_j^t$$

$$U_j^t = \frac{\sum_i I_{ji}^t}{\sum_k I_{jk}^t + F(j,t) + E(j,t)} * \left(1 - \beta_j^t\right) V_j^t$$

where t indicates time, D_j^t and U_j^t indicate the value added of downstream and upstream, I_{ij}^t indicates the inputs from i to j, V_j^t indicates the value added of j, $E(j,t)$ and $F(j,t)$ indicate the exports and final demand of j, excluding imports and exports. We take fully bioeconomy sectors as 100% bioeconomy, partly bioeconomy sectors include the upstream and downstream effects, and non-bioeconomy sectors are not taken into account. Also, we adopt the same definition, scope, classification and data as Cingiz et al.

Figure 7 demonstrates the results of the Chinese bioeconomy value added measured by HEM, the input-based method and the up- and downstream method. The three results see the same trends, increasing from 1995 to 2015, and fluctuating between 2015 and 2018. The results of HEM and the input-based method almost have the same size from 1995 to 2011, and the results of the up- and downstream method are always the biggest

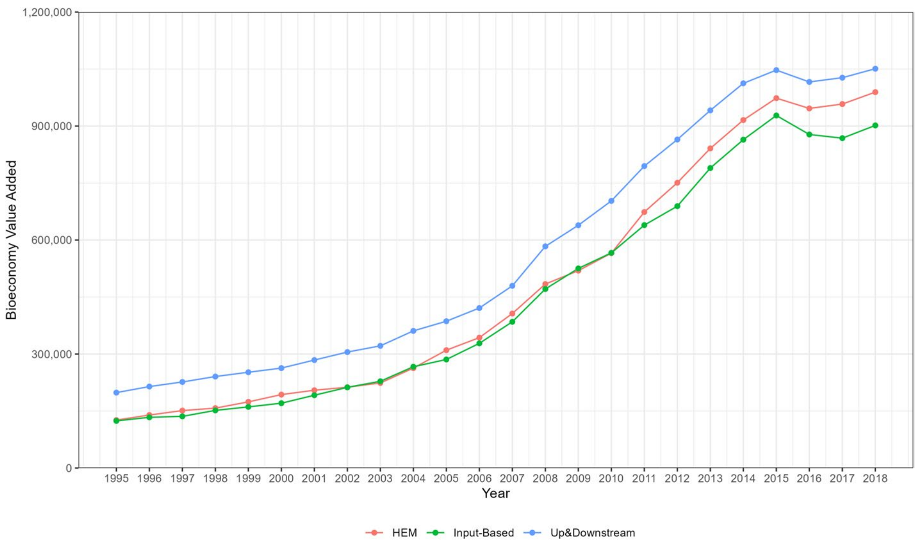

Fig. 7 The Chinese bioeconomy value added measured by HEM, the input-based method and the up- and downstream method (1,000,000 dollars)

throughout these years, approximately 57% and 60% larger in 1995 and 6% and 17% larger in 2018 than HEM and the input-based method.

4.4 Interpretations of the methodological comparison

To perform the comparison, we simplify our model by considering a two-sector economy in Table 5.

Let Sector 1 represent a fully bioeconomy sector, and Sector 2 represents a non-fully bioeconomy sector.

For HEM, we only classify sectors into fully and partly bioeconomy sector, so Sector 2 is a partly bioeconomy sector. In HEM, we remove z_{11}, z_{12} and z_{21} and get the bioeconomy value added

$$VA(HEM) = \left(\frac{f_1}{x_1} \frac{z_{11}z_{22} - z_{11}x_2 - z_{12}z_{21}}{(x_1 - z_{11})(x_2 - z_{22}) - z_{12}z_{21}} + f_2 \frac{z_{12}}{(x_1 - z_{11})(x_2 - z_{22}) - z_{12}z_{21}} \right) v_1 + \left(f_1 \frac{z_{21}}{(x_1 - z_{11})(x_2 - z_{22}) - z_{12}z_{21}} + f_2 \frac{z_{12}z_{21}}{((x_1 - z_{11})(x_2 - z_{22}) - z_{12}z_{21})(x_2 - z_{22})} \right) v_2 \tag{5}$$

For the up- and downstream method and the input-based method, Sector 2 could be a partly bioeconomy sector or a non-bioeconomy sector. If Sector 2 is a partly bioeconomy sector, we could get the bioeconomy value added for the up- and downstream method is

$$VA(UD) = v_1 + \left(\frac{z_{12}}{x_2} + \frac{z_{21}z_{22}}{x_2(z_{21} + z_{22})} \right) v_2 \tag{6}$$

The input-based method bioeconomy value added is

$$VA(IN) = \frac{z_{11}z_{12} + z_{11}z_{22} + z_{12}z_{21}}{(z_{11} + z_{21})(z_{12} + z_{22})} v_1 + \frac{z_{12}(z_{12} + 2z_{22})}{(z_{12} + z_{22})^2} v_2 \tag{7}$$

If Sector 2 represents a non-bioeconomy sector, the bioeconomy value added for the up- and downstream method and the input-based method will be

$$VA(UD) = v_1 \tag{8}$$

$$VA(IN) = \left(\frac{z_{11}}{z_{11} + z_{21}} \right) v_1 + \left(\frac{z_{12}}{z_{21} + z_{22}} \right) v_2 \tag{9}$$

Table 5 A two-sector input–output table

	Sector 1	Sector 2	Final Demand	Total
Sector 1	z_{11}	z_{12}	f_1	x_1
Sector 2	z_{21}	z_{22}	f_2	x_2
Value Added	v_1	v_2		
Total	x_1	x_2		

The primary difference is the sectoral classification. All sectors are classified into fully bioeconomy sectors and partly bioeconomy sectors in HEM, while other two methods also have non-bioeconomy sectors. Equations (5)–(9) show that all measurements of the bioeconomy value added could be simplified as the weighted sectoral sum. It is evident that HEM has more comprehensive value added weights. Upon comparison of Eqs. (5)–(7), we can see that the input-based method does not consider the sectoral total output as x_1 or x_2 does not exists in Eq. (7), while the other two methods do. Similarly, upon the comparison of Eqs. (5)–(9), it is clear that the up- and downstream only includes fully and partly bioeconomy sectors, while HEM and input-based methods also include value added, output or intermediate uses of non-bioeconomy sectors.

5 Discussions

The bioeconomy can drive sustainable development by fostering innovation and promoting a transition to sustainable production and consumption patterns. Monitoring its socioeconomic performance is essential for evaluating progress and identifying improvement areas. Achieving meaningful change, however, requires not only new policies and interventions but also a societal shift towards sustainable practices. Measuring the bioeconomy is key to assessing its economic value, tracking its sustainability impacts, informing policy decisions, and facilitating global comparisons.

In this paper, we find that China has consistently held the largest bioeconomy value added since 2011. One reason is that China has undergone rapid economic development in recent decades and currently boasts the second-largest economy. What's more, China has supported the development of the bioeconomy for years, through policies to promote industrial development and funds to encourage biotechnology research. Some public reports show a big increase in some subsectors of the bioeconomy. From 2010 to 2015, the bioindustry output increased by 22.9% annually (The State Council of the People's Republic of China, 2012). The average growth of the pharmaceutical Contract Manufacture Organization market in China is 17.4% from 2012 to 2017 (Ministry of Science & Technology of the People's Republic of China, 2016). But in our results, especially when comparing the growth rates of the total economy and the bioeconomy, we cannot figure out which grows faster, and whether the bioeconomy policy is more effective. Different definitions, scopes or included sectors could yield varying results.

Moreover, among the ten countries examined, both China and India, as non-OECD countries, exhibit larger bioeconomy value added percentages ranging between 15 and 19% compared to the other eight OECD countries, all of which have percentages below 11%. This observation is not surprising, given that China and India have larger shares of primary industry—Agriculture, hunting, forestry and Fishing and aquaculture. China's percentage of 2018 stands at approximately 7.35%, while India's is around 17.24%. In contrast, the eight OECD countries have much smaller percentages: 0.96% (US), 1.06% (Japan), 0.74% (Germany), 0.64% (UK), 1.82% (France), 2.19% (Italy), 2.03% (Canada), and 1.91% (Korea).

Furthermore, we compared the results obtained from the HEM with other methodologies. we find that the HEM and the input-based method produce similar outcomes for China, with both methods yielding significantly lower results compared with the up- and downstream approach. The main difference between these methods lies in their underlying assumptions. The objective of HEM, based on Leontief input–output tables, is to analyze how much the economy system would change if the bioeconomy connections were removed from that economy. HEM assumes a linearity so that scale are not considered in the calculation. The input-based method assumes perfect substitutability, that is, the bio-based inputs of all inputs were used to calculate the partly bioeconomy sectors. However, the bio-based proportions are hardly determined for many products (Kuosmanen et al., 2020) and it only includes the downstream and may underestimate the contribution of the bioeconomy. The up- and downstream method considers both upstream and downstream effect for partly bioeconomy sectors (Cingiz et al., 2021), and its results are higher than the other two methods.

HEM is quite different from methodologies using indicators. Indicator-based methodologies typically rely on predefined metrics or indicators (such as GDP, energy efficiency rates, or carbon emissions per capita) to assess and compare economic, environmental, or energy systems. These approaches are often descriptive, using measurable variables to track trends, evaluate performance, or benchmark progress against targets. Many researchers use indicator-based methodologies to evaluate the bioeconomy. D'Adamo et al. (2020) proposed a socio-economic indicator to assess the performance of the bioeconomy sectors in Europe. This framework utilizes parameters such as turnover, value added, and workforce, and define nine subsectors into the bioeconomy. Kardung and Drabik (2021) selected 41 indicators to investigate the bioeconomy progress of ten EU countries. These indicators included value added, investment, employment, research and development, renewable energy, and more. D'Adamo et al. (2024) proposed a composite framework with 105 indicators to measure the well-being for Italian regions. O'Brien et al. (2017) introduced a comprehensive monitoring system incorporating indicators and targets that address environmental, economic and social dimensions of the bioeconomy, with a particular emphasis on global land use. While indicator-based approaches provide detailed and quantifiable insights, they are highly dependent on the availability of high-quality, extensive datasets spanning numerous variables. This reliance necessitates significant time and resources for data collection, regular updates, and maintenance to ensure continued relevance.

In contrast, HEM uses a systems-based approach that integrates input–output analysis with hypothetical scenarios. Instead of focusing on fixed indicators, HEM simulates interactions and interdependencies across sectors to model the impact of hypothetical changes. This enables a more structural analysis of how various components of the economy might respond to external factors, providing insights that go beyond what is possible with static, indicator-driven methods.

6 Conclusions

In this paper, we utilized HEM to measure bioeconomy. We extract intersectoral transactions categorized as bioeconomy-related from input–output tables, based on existing literature. By comparing the extracted transactions before and after this process, we determine the output of the bioeconomy. Subsequently, we employ the value-added coefficient matrix to convert the output into value added. OECD input–output statistics are used to compare the bioeconomy value added, percentages and growth rates of the ten biggest countries from 1995 to 2018. Our analysis reveals that China has consistently held the highest bioeconomy value added since 2011, and two none-OECD countries, China and India, has much higher bioeconomy shares than the other OECD countries.

Indeed, HEM can be extended to calculate various indicators such as turnover, employment, or greenhouse gas (GHG) emissions. Taking employment as an example, researchers can apply HEM to extract the bioeconomy output and subsequently convert it into employment figures using an employment coefficient matrix. This matrix is derived by dividing the employment data for each industry by its respective output. In the context of this paper, we utilized the OECD input–output tables, which consist of 45 industries, to measure bioeconomy value added. To calculate employment within the bioeconomy, access to employment data for these specific 45 industries is necessary to construct the employment coefficient matrix. It is worth noting that input–output data and employment statistics often lack harmonization. The availability of consistent and compatible data across different sources is crucial to ensure accurate calculations and reliable results.

One notable advantage of the HEM is that it assesses the bioeconomy by considering the interconnectedness among sectors across the entire economy, offering a unique perspective compared to other methodologies. The societal benefits of employing HEM to measure the bioeconomy lie in its ability to evaluate key determinants of economic contributions and intersectoral linkages. By identifying the specific sectors driving bioeconomy value-added, this research provides valuable insights for policymakers to design targeted strategies for sustainable economic growth. Furthermore, it helps stakeholders understand the societal and economic impacts of bio-based industries, including their roles in job creation, resource efficiency, and contributions to the Sustainable Development Goals, particularly those focused on responsible production and consumption, climate action, and economic development. This comprehensive assessment promotes informed decision-making and enhances the alignment of bioeconomy initiatives with societal well-being.

However, the HEM has several limitations that warrant consideration when applied in input–output analysis. First, as HEM is based on Input–Output analysis, they inherit several limitations of this framework. They assume a linear and static economic structure, failing to account for the dynamic nature of real-world economies. Changes in technology, consumer behavior, and market dynamics are excluded, which can oversimplify complex systems. Additionally, HEM highly depends on hypothetical scenarios, which may not accurately reflect real-world conditions. This reliance introduces uncertainties and can result in outcomes that do not fully predict actual economic responses. This method may also overestimate the impact of removing a sector, as it does not consider how economies adapt through resource reallocation or alternative means of fulfilling demand. Another limitation is HEM's narrow focus on direct and indirect economic linkages, often neglecting externalities such as environmental or social effects, which are critical for comprehensive evaluations. Furthermore, the accuracy of its results depends heavily on the quality and granularity of input–output data, with outdated or aggregated datasets potentially skewing findings. Despite these limitations, HEM remains a valuable tool when complemented by dynamic models and alternative methodologies. By integrating broader perspectives and ensuring high-quality data, HEM can provide insightful analyses for policymakers and researchers exploring economic interdependencies.

Appendix

The sectoral classifications are based on OECD Input–Output tables.

OECD Industry Code	ISIC 4 corresponding Division	Description	Classification
D01T02	01,02	Agriculture, hunting, forestry	F
D03	3	Fishing and aquaculture	F
D05T06	05,06	Mining and quarrying, energy producing products	P
D07T08	07,08	Mining and quarrying, non-energy producing products	P
D9	9	Mining support service activities	P
D10T12	10,11,12	Food products, beverages and tobacco	F
D13T15	13,14,15	Textiles, textile products, leather and footwear	P
D16	16	Wood and products of wood and cork	F
D17T18	17,18	Paper products and printing	F
D19	19	Coke and refined petroleum products	P
D20	20	Chemical and chemical products	P
D21	21	Pharmaceuticals, medicinal chemical and botanical products	P
D22	22	Rubber and plastics products	P
D23	23	Other non-metallic mineral products	P
D24	24	Basic metals	P
D25	25	Fabricated metal products	P
D26	26	Computer, electronic and optical equipment	P
D27	27	Electrical equipment	P
D28	28	Machinery and equipment, nec	P
D29	29	Motor vehicles, trailers and semi-trailers	P
D30	30	Other transport equipment	P
D31T33	31,32,33	Manufacturing nec; repair and installation of machinery and equipment	P
D35	35	Electricity, gas, steam and air conditioning supply	P
D36T39	36,37,38,39	Water supply; sewerage, waste management and remediation activities	P
D41T43	41,42,43	Construction	P
D45T47	45,46,47	Wholesale and retail trade; repair of motor vehicles	P
D49	49	Land transport and transport via pipelines	P
D50	50	Water transport	P
D51	51	Air transport	P
D52	52	Warehousing and support activities for transportation	P
D53	53	Postal and courier activities	P
D55T56	55,56	Accommodation and food service activities	P
D58T60	58,59,60	Publishing, audiovisual and broadcasting activities	P
D61	61	Telecommunications	P
D62T63	62,63	IT and other information services	P
D64T66	64,65,66	Financial and insurance activities	P
D68	68	Real estate activities	P
D69T75	69 to 75	Professional, scientific and technical activities	P
D77T82	77 to 82	Administrative and support services	P

OECD Industry Code	ISIC 4 corresponding Division	Description	Classification
D84	84	Public administration and defence; compulsory social security	P
D85	85	Education	P
D86T88	86,87,88	Human health and social work activities	P
D90T93	90,91,92,93	Arts, entertainment and recreation	P
D94T96	94,95,96	Other service activities	P
D97T98	97,98	Activities of households as employers; undifferentiated goods- and services producing activities of households for own us	P

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Data availability The dataset is available at the URL: https://www.oecd.org/sti/ind/input-outputtables.htm.

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