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Research article

A decision support procedure for the bioeconomy transition: A colombian case study

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ABSTRACT

An increasing number of countries and regions consider the bioeconomy transition a strategic policy priority. When approached through the lens of a circular economy perspective, investments in bioeconomy have the potential to enhance resource utilisation efficiency, preserve biodiversity and ecosystems, and foster sustainable development with low emissions. At the same time, if requirements and contextual factors of bioeconomy strategies are not formally analysed, bioeconomic investments might lead to unintended negative consequences. This paper proposes a decision support procedure to design, assess, prioritise, and monitor bioeconomy investments and policies. The flexibility and scalability of our decision support procedure is tested in Colombia to foster a regional and local transition to bioeconomy initiatives that consider the local capital assets and the stakeholders' views. The heterogeneous character of the Colombian environment, economy, society and culture represents an ideal condition to test the strength of the decision support procedure to promote bioeconomy in low and middle-income countries. Our empirical results highlight the benefit of adopting a formal assessment framework that includes strategic national indicators, regional features and stakeholders' views. In terms of the Colombian regional bioeconomy ambitions, we highlight the need for expanding knowledge hubs and participatory stakeholder networks and buttressing appropriate financial mechanisms.

1. Introduction

During the last decade, bioeconomy (BE) has attracted increasing interest in policy circles and in the governance agenda globally (Aguilar et al., 2019; Dietz et al., 2018). International and national organizations in the public and private sector have acknowledged that BE can play a positive role in transitioning towards a more resource-efficient and low-emission economy (Dietz et al., 2018; Ingrao et al., 2016; El-Chichakli et al., 2016).

But while BE can be a necessary step towards sustainability objectives, it is not sufficient on its own. Different authors have expressed the concern that the BE transition can jeopardize the Sustainable Development Goals (SDGs) especially if not framed with sustainability in mind (Ronzon and Sanjuán, 2020; Biber-Freudenberger et al., 2018; Heimann, 2019). The 17 sustainable development principles can be put into three sets: economic, environmental, and social. In total they aim to ensure the ongoing maintenance over time of physical, natural and social capital stocks and their continuous supply of services essential for economic progress and increased wellbeing (WCED, 1987). However, the risk is that BE strategies may simply follow a bio-technological pathway, where highly engineered products and processes replace the natural capital to increase gross domestic product (GDP) and employment. Alternatively, BE strategies can be overly bio-ecological, where conservation and nature restoration are achieved at the expenses of the social and man-made capital (Bugge et al., 2016). Thus, BE needs to be supplemented by other sustainability concepts such as the Circular

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Economy (CE) principles (D'Amato and Korhonen, 2021; McGlade et al., 2020) and the social and environmental boundaries promoted by approaches such as the doughnut economy (Warnecke, 2023; Wahlund and Hansen, 2022; Raworth, 2017). If framed within the principles of CE, supported by regional and national evidence-driven information, and based on stakeholders' involvement, BE investments can follow a pragmatic bio-resource approach where the reduction of fossil-fuel dependency, the creation of value added and the enhancement of biodiversity and ecosystems are jointly developed within the key pillars of sustainable development (Salvador et al., 2021; Stegmann et al., 2020; European Commission, 2018).

In this sense, BE governance needs to account for conflicts, trade-offs, and complementarities across policy domains considering different geographical scales and relying on comprehensive information related to the many factors driving the success and sustainability of BE initiatives (Muscat et al., 2021). However, BE implementations and assessments so far have overlooked the practical, contextual, and data-driven requirements of a sustainable circular BE governance and the related decision support procedures needed to plan, develop and monitor it. Focus has mostly been on monitoring frameworks limited in scope and scalability because applied at the macro-scale (D'Amato and Korhonen, 2021; Morone, 2018; O'Brien et al., 2017), assessed from a theoretical point of view (Bugge et al., 2016; Vivien et al., 2019; Kircher, 2021), based in middle-high income countries (Wensing et al., 2019; Kershaw et al., 2021; Dieken et al., 2021; González-Castaño et al., 2021), or focussed on single products/processes (e.g., Donner et al., 2022; Bortoloto Damasceno Barcelos et al., 2021). The lack of coherent, comprehensive, and replicable decision support procedures that guide circular BE initiatives can represent a serious threat for the achievement of SDGs especially in countries with weak political and legislative systems.

Our paper fills these gaps in the BE transition and governance literature by proposing a decision support procedure to guide potential CE-BE investments and policies. The paper revises the Balance Sheet Approach (BSA) (Turner, 2016; Turner et al., 2019; Schaafsma et al., 2021; Scharin et al., 2016) with an application to Colombia. The BSA is a process and set of tools to fully appraise BE projects, policies, or courses of action. Within the BSA we bring together evidence on the national scale priorities and the underpinning regional scale capital assets (physical, human, natural and social) that are necessary foundations for a BE-led investment path which is inclusive and coherent with the SDGs.

The deployment of a BSA decision support procedure enhances the capacity to plan and monitor investments and to avoid unintended consequences especially in low and middle-income countries. Our approach is tested on a case study in Colombia, a country characterised by a highly biodiverse environment and a multi-cultural society. Our case study reveals the importance of following a decision support procedure to unfold local diversity and foster a shared vision for successful BE planning. To assess the national and regional economic, environmental, and social conditions we conduct a capital assets check using the statistical tool of the cluster analysis. This national and regional analysis, coupled with a synthetic visual analysis for the single Colombian departments, reveals the opportunities and challenges to promote BE investments. These findings are subsequently enriched by stakeholders' dialogue initiatives which identify the possibilities for and barriers to a BE development pathway. Our empirical findings can further support other countries with weak institutions, high levels of poverty and inequality, but also with a high value and very diverse in situ natural capital stock.

This paper is divided as follows. Section 2 examines the concepts of BE and CE as they have evolved in the literature and the required transition process. Section 3 sets out our methodology and proposed decision support procedure for CE-BE project/policy appraisal and Section 4 applies it to our Colombia case study. Section 5 contains a discussion and Section 6 offers some recommendations, followed by conclusions in Section 7.

2. Bioeconomy within a circular economy framework

The BE concept broadly refers to any industrial and economic sector that produces, manages, and otherwise exploits biological resources and related services. As summarised in Table 1, a range of economic sectors and activities can fit this definition, ranging from traditional (e.g., agriculture, forestry) to more high-tech sectors (e.g., bio-intelligence, genetic engineering) (Sasson and Malpica, 2018; Haarich, 2017; Vivien et al., 2019; Mougenot and Doussoulin, 2022; Priefer et al., 2017; Meyer, 2017; Bugge et al., 2016; Staffas et al., 2013).

Over time, more nuanced interpretations have emerged. Bugge et al. (2016) proposed dividing BE strategies into three ideal pathways: (i) the bio-technological pathway which aims to support GDP-focused economic growth and job creation by leveraging biotechnological innovation and market development; (ii) the bio-resource pathway which seeks to combine economic progress with stronger sustainability constraints; and (iii) the bio-ecological pathway which puts biodiversity protection and soil degradation avoidance before economic growth. Nevertheless, these pathways are best viewed as part of a spectrum without sharp boundaries. Synergies and overlaps in BE pathways emerge due to competition for biomass, natural resources, public support, government spending, and market shares; as well complementarities and knowledge spillovers can emerge for infrastructures, supply chains and human resources (Wydra et al., 2021).

Independently of the pathway, all BE initiatives need to fit within circularity principles to limit their impact on natural and social capital assets. A circular BE model reduces the economy's reliance on resource exploitation and encourages bio-waste value creation through its cascade use (Salvador et al., 2021; Kershaw et al., 2021; D'Amato and Korhonen, 2021; McGlade et al., 2020). But it can be further argued that the implementation of a circular BE needs to be embedded within wider constraints. These constraints relate to economic, environmental and social principles to secure a sustainable trajectory and the achievement of SDGs. Social and environmental boundaries need to be imposed to define the 'safe' and 'fair' space within which the BE sits (Rockström et al., 2009; Steffen et al., 2015). For this reason, an Expanded Circular BE concept (Turner et al., 2019) should be considered which is constrained by two 'boundary' conditions: an upper environmental boundary and a lower 'social floor' linked to a maximum acceptable level of wealth inequality, and minimum acceptable level of deprivation[1] (Fig. 1).

The so called 'social limits to growth' argumentation has a long history but in the last sixty years or so has gradually permeated into economic and environmental policy discussions. The position taken is that fast growing economies (in GDP terms) will not necessarily result in increased levels of social welfare and wellbeing, either at the individual level or more broadly through communities and regions (Mishan, 1978; Daly, 1973; Hirsch, 1976; Raworth, 2017; Hansen, 2022). Most recently, the position has been buttressed by analysis showing that inequality is often associated with inefficiencies in the economy which require correction (Stiglitz, 2013). A social dimension in addition to an environmental boundary highlights the importance of wellbeing, distributional equity, justice and democracy concerns as development proceeds. These concerns emphasise the need for inclusion and participation in decision making. So, BE value chains need to be established through co-creation involving local communities and indigenous groups (McGlade et al., 2020). The social boundary has an economic dimension as well. Growing inequality is associated with growing inefficiencies and less productive economies, which also display increased stress, poor health, and low levels of social mobility (Stiglitz et al., 2010; Drupp

[1] The standard Circular Economy is expanded to include plural values in nature as well as fair distribution of benefits across current and future generations. Therefore, economic growth is bounded by social and environmental limits.

Table 1
A summary of economic sectors and subsectors considered linked to bioeconomy.

Sector	Biodiversity and Ecosystem Services	Ecological Engineering	Sustainable and Intensive Agriculture	Forestry and Silviculture	Foods and Beverages
Examples of Subsectors	Ecotourism Nature scientific tourism Payments for ecosystem services Carbon sinks Natural Ingredients Medicinal plants Bioprospecting	Eco-designs Bioremediation Ecological restoration Natural resource management Waste management	Agroforestry No-till farming Organic agriculture Regenerative agriculture Pasture intensification Precision farming Nano-agriculture	Timber and fibre products Ornamentals Plants exuding gums and resins Natural dyes and colorants	Functional foods Medicinal foods Nutraceuticals Dietary supplements Gastro-botany
Sector	Biofuels	Industrial Biotechnology	Biomedicine	Bio-intelligence	Genetical Engineering
Examples of Subsectors	Bioethanol Biodiesel Biogas Bio-methanol Biobutanol	Biocosmetics Industrial microbiology Bioplastics Bio-textiles Bio-lubricants Agricultural bio-inputs	Tissue engineering and cell therapy Personalized Medicine Genomic Medicine Nanomedicine Biopharmaceuticals Biosimilars	Omics Studies and Population Genetics Bioinformatics Biological data Bionics biomimicry	Genetic selection methods Reproductive technologies Genetically modified organism Gene therapy

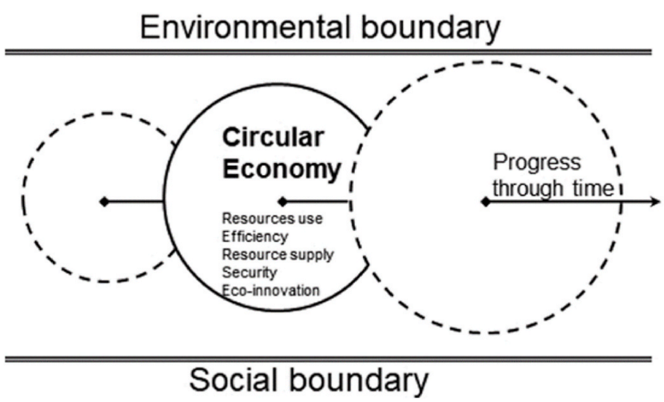

Fig. 1. Expanded circular economy-bioeconomy. Source: Turner et al. (2019).

et al., 2018).

The Expanded CE-BE allows for a broader vision of economic progress which produces sustainable economic development by taking a precautionary approach to 'critical' natural capital protection, thresholds, and tipping points, and by increasing societal well-being. Therefore, the BE governance should be holistic enough to account for conflicts, trade-offs and complementarities across BE development pathways and allow an understanding of the factors driving the success and sustainability of BE initiatives.

Some of the most pressing considerations and settings that should be underpinning the transition to BE initiatives are.

(i) endowment considerations, related to the availability, quality, and classification of natural, social, human, manufactured and financial capital which determine the feasibility and attainability of different transition pathways, and
(ii) sustainability considerations, related to potential impacts of BE initiatives on social, economic and environmental targets which can constrain the degree at which the diverse forms of capital can be sourced and utilised sustainably and efficiently, in order to achieve environmental, social and economic targets.

Not considering these factors within the design, implementation, and monitoring of BE initiatives increases the risks of failure and of an inefficient allocation of resources (Kershaw et al., 2021; Devaney and Iles, 2019).

3. A decision support procedure for the bioeconomy transition

The sustainable BE transition necessitates an enabling portfolio of comprehensive and coherent green investments targeted at resource and energy use, efficiency gains and waste reduction, together with health, education, and other environmental, socioeconomic, and cultural assets improvement (Hinderer et al., 2021). The green investments portfolio and policy decisions need to be underpinned by a systematic assessment and monitoring of environmental and social consequences of economic changes (D'Amato and Korhonen, 2021; Bracco et al., 2019; O'Brien et al., 2017). At the macro-level, natural, man-made, social, and human capital will determine the variety of BE strategies available for a country. National accounts, natural capital accounts and wealth accounts can assist in planning and monitoring BE initiatives and their impacts on SDG objectives and the country's welfare pathway (Talberth and Weisdorf, 2017; Turner et al., 2019). These initial economic, social and environmental conditions represent the pre-requisite for promoting and steering specific BE initiatives. This existing evidence (Fig. 2, panel A – Assessment) serves as an initial assessment and information base that feeds into the development and balancing of individual BE initiatives (either sectoral- or geographical-specific).

At the level of individual BE initiatives, there will need to be an appropriate set of appraisal criteria, indicators and implementation measures focused on resource efficiency and eco-efficiency gains (Bracco et al., 2019; Kardung et al., 2021). Measures will include, among others, carbon reduction instruments, soil nutrient and carbon retention measures, grazing land quality enhancement, sustainable yield management of renewable energies, water and biodiversity conservation and management measures. It is also needed that potential unintended rebound effects of BE projects are monitored, ensuring that policy measures and green investments are adequately targeted (Kershaw et al., 2021; Stark et al., 2022; El-Chichakli et al., 2016) and that the risk of allocating resources inefficiently is minimised (Devaney and Iles, 2019). This can be achieved through a decision support procedure, that is the set of tools, analyses and processes to follow for planning, assessing and monitoring specific BE initiatives. The BE decision support procedure proposed here is the Balance Sheet Approach (BSA) (Turner, 2016) (Fig. 2, panel B – Balancing). The BSA will guide the whole policy process from the designing to the actual implementation of specific BE initiatives. It will formally and consistently arrange information including views and preferences of the stakeholders involved, which represent a key factor in the success of BE investments especially at the local/regional scale (Niang et al., 2022). The trade-off analysis of stakeholders' views and values will capture the social dimension of BE initiatives and anticipate unexpected effects on communities and groups. This ensures that macro-level indicators can be re-assessed and

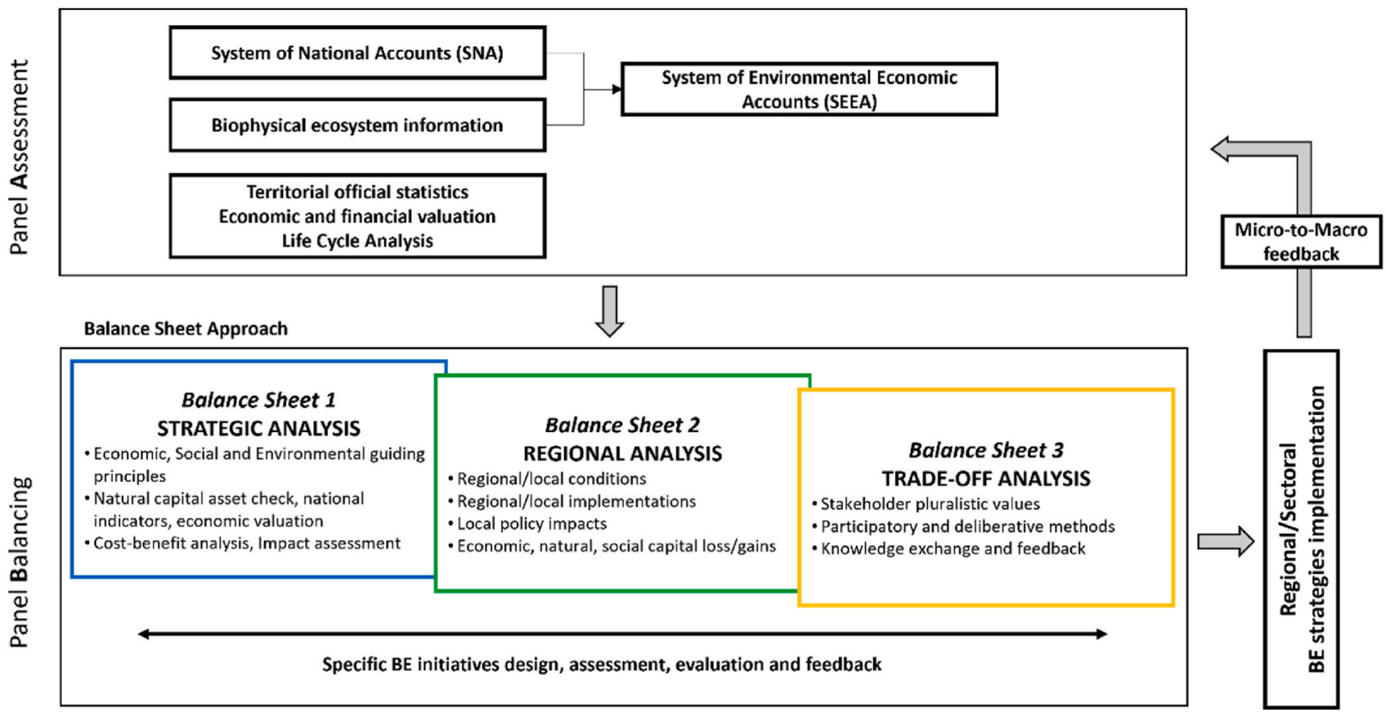

Fig. 2. BE decision support procedure. Source: adapted from Turner (2016).

re-balanced to accommodate specific social dimensions (e.g., indigenous ancestral values) that are difficult to capture with standard assessment tools and indicators used in the strategic analysis and the regional analysis in Fig. 2.

Our decision support procedure addresses gaps and expands on the BE governance and policy debate. The BE literature has mainly focused on a global or national level perspective, neglecting the heterogeneity of landscapes and regional/local perspectives (Sanz-Hernández et al., 2019; Luhas et al., 2021; Kershaw et al., 2021; Laibach et al., 2019; Wohlfahrt et al., 2019; Dieken et al., 2021; Meyer, 2017). The BE-BSA is scalable, designed to best suit the local context and formally includes the local stakeholders' perspective as will be shown in the Colombian case-study application. In addition, it is inclusive, flexible and multi-dimensional in collating different information and tools, which is a lacking feature of previous BE appraisals (Kershaw et al., 2021; Wohlfahrt et al., 2019; Laibach et al., 2019; Sanz-Hernández et al., 2019). An application of the BE-BSA procedure for Colombia is presented in the next section.

4. Setting a decision support procedure for Colombian regional bioeconomy strategies

The potential for a Colombian BE strategy has historically remained low on the national policy agenda due to the long-lasting internal armed conflict. However, in the post-conflict context BE has been increasingly seen as a new and powerful engine for the development of the country (Hernández and Schanz, 2019; Rojas-Jimenez, 2021). In 2018, the Colombian government produced a series of guidelines and policy recommendations for BE development. These recommendations were later collected in the '*Misión de Bioconomia*', launched in 2020 as the national BE strategy (Minciencias, 2020). Building upon five strategic areas (biodiversity and ecosystem services, bio-intelligence, productive and sustainable agriculture, biomass and green chemistry, health and well-being) the '*Misión de Bioconomia*' aims to promote the socioeconomic development of Colombia using science, technology, and innovation to create high-value bioprocesses and bioproducts. Through this strategy the Colombian government expects to generate over 2.5 million jobs and over 500 bio-products (DNP, 2020). Overall, the expectation is that BE will represent 10% of the national GDP by 2030. The '*Misión de Bioconomia*' however was not without its critics because it was seen as a mainly centralised top-down process which did not emphasise biodiversity conservation goals nor the interests of local stakeholders and indigenous communities (Sasson and Malpica, 2018; Hernández and Schanz, 2019). How can the '*Misión de Bioconomia*' strategy better match the specific economic, social and environmental characteristics of Colombia and its diverse local contexts?

To answer this question, we deploy the decision support procedure proposed in Section 3 i.e., the BE-BSA. The specific tools, analyses and processes used in this case-study exemplify those that can be used within a BSA. The selection of tools and methods is driven by data access and availability.

The feasibility of the BE transition for Colombia is firstly analysed at the national level to subsequently focus on four specific regions (Antioquia, Valle del Cauca area, Coffee Zone and Orinoquía, see the Supplementary Material for socio-economic information of the regions).[2]

In the strategic analysis (Fig. 3), the extent to which BE initiatives, investments and impacts are compatible with the three pillars of sustainability (environmental, economic, and social) is assessed. The methodological tools deployed at this stage for the Colombian case study are an asset check, covering the capital endowment at macro-level, and a cluster analysis to categorise the potential regional BE development paths.

In the regional analysis (Fig. 3), a local impact analysis is undertaken focussing on a further disaggregation of the evidence gathered at the previous stage. In the regional analysis, the focus shifts to local implications of the BE implementation, considering indicators of economic activity (e.g., income distribution, employment, public spending), natural capital (e.g., biodiversity status, ecosystem protection measures), and socio-cultural aspects (e.g., community identity and trust, social

[2] The four selected regions were the focus of the project 'Meeting policy challenges for a responsible biodiversity-based bioeconomy in Colombia' funded by the UK Research and Innovation Global Challenge Research Fund.

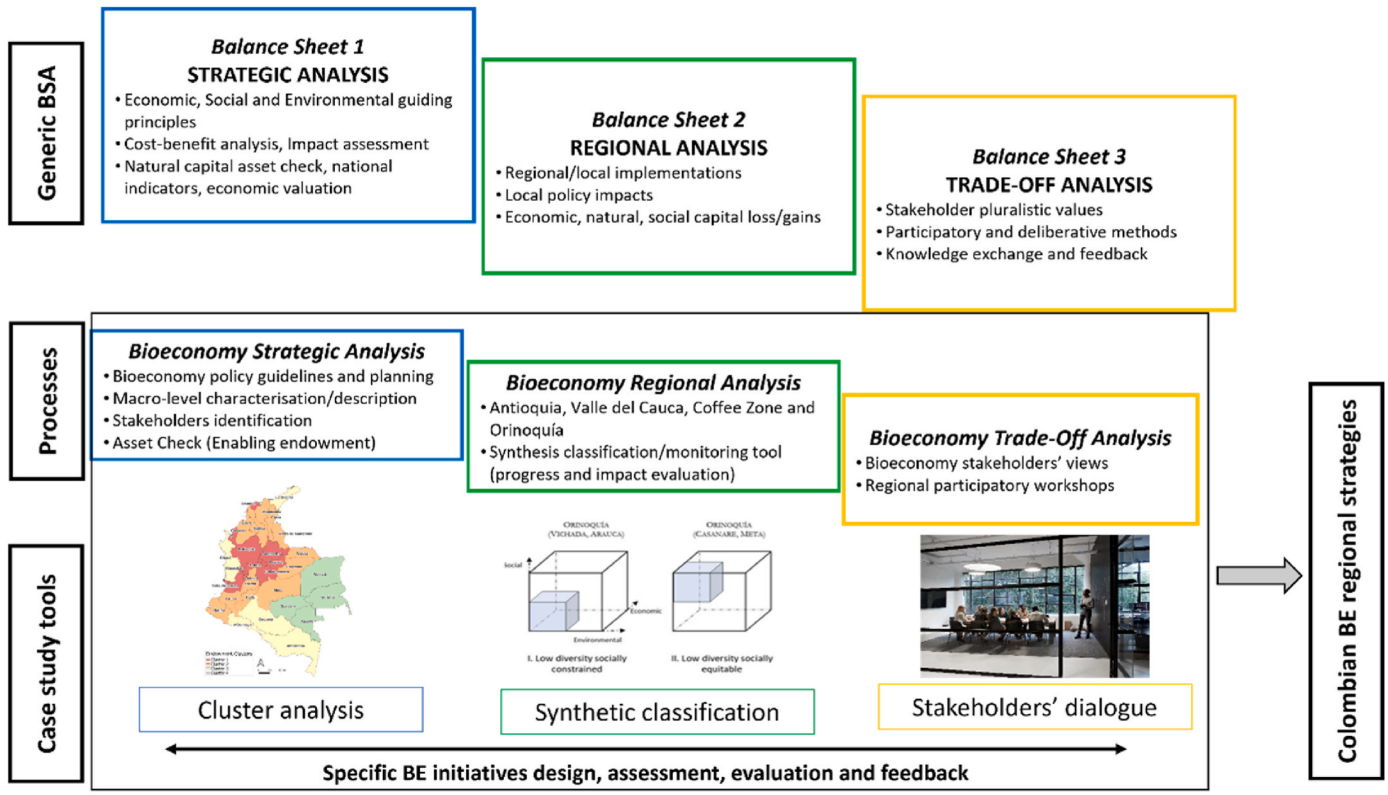

Fig. 3. BE decision support procedure.

inclusion, diffusion of knowledge). The methodological tool used in our case study is a three dimensional visual representation of departmental-level sustainability pillars. Finally, the trade-off analysis focusses on negotiations, pluralistic values and views of the stakeholders involved. This requires a detailed understanding of the different (and sometimes contesting) stakeholders' views, attitudes, and motivations towards prospective BE projects. Here, deliberative methods of stakeholder participation are key tools, and we deployed stakeholder consultations to map their views and perspectives.

4.1. Strategic analysis: national asset check

The first step of our analysis is the asset check. There is no clear consensus on the most appropriate indicators for designing, assessing and monitoring the BE transition given its complexity and cross-sectoral nature (see for example, O'Brien et al., 2017; Bracco et al., 2019). Previous studies differ widely, ranging from a few selected indicators (e.g., Ronzon and M'Barek, 2018; D'Adamo et al., 2020) to frameworks using a large number of variables (e.g., Kardung and Drabik, 2021). In our case study, the selection of the indicator variables as proxies for economic, social and environmental assets (and their condition) considers (i) the literature on asset endowment, enabling or constraining BE factors at national and local level, (ii) the availability of updated and open access datasets from national official sources, and (iii) the need to retain a manageable number of indicators. Table 2 summarises the most relevant BE endowment elements as found in the literature, and the corresponding shortlisted nine headline indicator variables.

A clustering approach (Everitt et al., 2011) is carried out at the department level to synthetise the information conveyed in the key indicators of Table 2. The cluster analysis is a well-known classification technique (Bartholomew et al., 2008) and is extensively used in many fields of application, including BE (Biber-Freudenberger et al., 2018). Moreover, the importance of BE clusters in driving a sustainable bio-based transition is increasingly acknowledged, including in the Colombian context (Johnson et al., 2022a; Stegmann et al., 2020). In our case, it allows for the identification of a set of macro-clusters based on observed similarities in economic, social and environmental conditions. The objective of the cluster analysis is to organise and classify regional indicators through a clear and repeatable process which identifies locations that share similarities in their economic, social and environmental measures. Cluster analysis involves using mathematical algorithms to group data points based on their similarities and helps to uncover patterns and relationships within a dataset, making it easier to understand and analyse large amounts of information. A partitioning cluster analysis with PAM algorithm is used here (Partitioning Around Medoids, Kaufman and Rousseeuw, 1990), which is a k-medoid type algorithm that provides clusters built around the most representative observation (one per cluster). PAM is less sensitive to outliers and noise in data than other partitioning methods.[3] A solution with four endowment clusters was found to be the best fit. The four clusters obtained are mapped in Fig. 4. Additional details on the clustering approach are reported in the Supplementary Material.

Cluster 1 groups most of the central Andean departments (Atlántico and Valle del Cauca), areas with big urban conglomerates and specialised economies (third sector, tourism, cattle ranching). It includes the Coffee Zone and the Antioquia area. This cluster is characterised by high connectivity and infrastructure development, and higher diversification of economic activities. It is also characterised by the highest density of R&D and scientific groups, the lowest diffusion of multidimensional poverty and by a highly diverse land use cover. Cluster 2, including most of the Atlantic departments, the Orinoco grassland area, and the

[3] A typical problem with cluster analysis pertains to validating the clusters obtained (Everitt et al., 2011). In our application, this is addressed through a preliminary assessment of the cluster tendency (Hopkins statistic, visual assessment of cluster tendency, elbow method, clustering power with differing number of clusters) and an additional in-depth exploration of the within-cluster differences using the synthesis tool reported in Section 4.2.

Table 2
Bioeconomy enabling endowment factors and corresponding indicators.

Endowment	Enabling factors	Indicator variables	Source
Economic			
Public finances	Public funds for start-up costs, innovation, market diffusion (Wohlfahrt et al., 2019; Wydra et al., 2021)	Department expenditures ($COL/capita)	Minhacienda (2018)
Logistic infrastructures	Transportation, communications, and IT systems (Wohlfahrt et al., 2019)	Paved highway (mt/km^2)	IGAC Instituto Geográfico Agustín Codazzi (2014)
Strength of value and supply chains	Diversification and strength of value chains (Wohlfahrt et al., 2019)	GDP diversity (Shannon index)[a]	DANE (2016)
Social			
Innovation propensity	Propensity to innovate (Bröring et al., 2020)	Internet coverage (% households)	DANE (2018a)
Strong social fabric	Sense of commitment, fairness and mutual trust (Kircher et al., 2018)	Multidimensional Poverty (% households) [b]	DANE (2018b)
R&D networks, Human resources	R&D institutions and networks (Kershaw et al., 2021, Bröring et al., 2020)	Scientific groups (n/million inhabitants) [c]	Minciencias (2019)
Environmental			
Biota	Biodiversity and biological resources (Bracco et al., 2019)	Protected areas (% total)	PNN Parques Nacionales Naturales de Colombia (2019)
Land cover	Land coverage patterns and land use (Bracco et al., 2019)	Land Cover diversity (Shannon index) [d]	IDEAM Instituto de Hidrología (2014)
Biomass availability	Availability of biomass (Robert et al., 2020)	Forests area (% total) [e]	Minagricultura (2019)

Notes.
[a] Diversification of the GDP across main economic sectors (agriculture, mining, industrial, public services, tertiary, transport).
[b] Used as percentage of households not multidimensionally poor, that is (1-Multidimensional Poverty).
[c] Scientific groups are those registered and accredited by the Department of Sciences.
[d] Shannon Index calculated from CORINE land cover data.
[e] Agricultural areas are not included because of the inability to disentangle extensive from more sustainable practices.

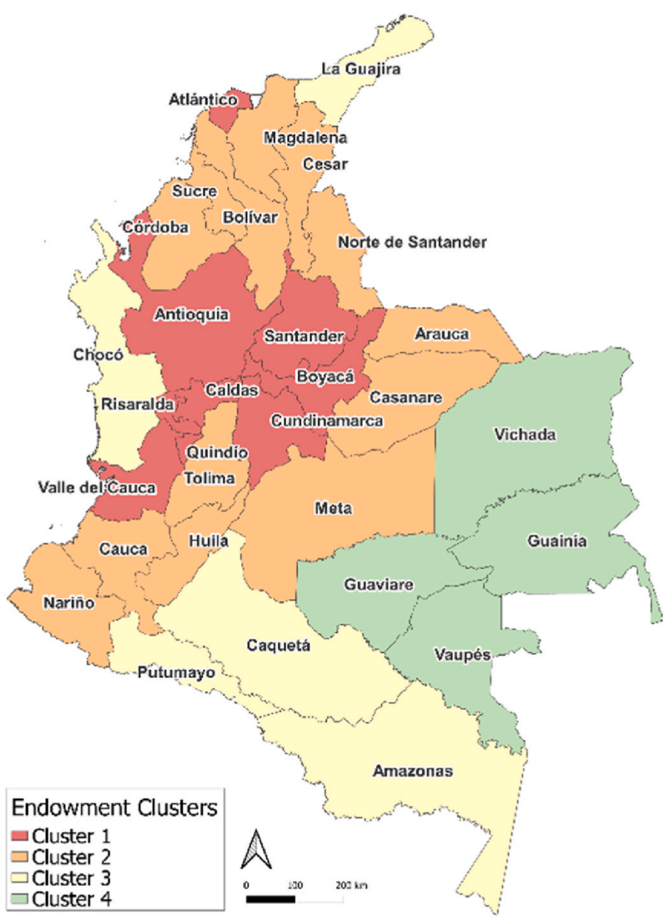

Fig. 4. Bioeconomy macro-clusters of Colombia based on endowment enabling factors.

departments located in the southern portion of the Andes, is characterised by a good level of connectivity and infrastructural development, a GDP derived from a wide range of activities, and land cover use diversity. It includes parts of the Coffee Zone and most of the Orinoquía. Departments in this cluster are contiguous to the central, highly urbanised and innovative Cluster 1, with potential positive spill overs between the two clusters.

Cluster 3, including the southern Amazon departments, Chocó on the Pacific coast and La Guajira on the Atlantic coast, is defined by the highest percentage of protected pristine forest and agricultural exclusion areas. While connectivity and infrastructural development are still lagging behind other departments, this cluster shows a good diffusion of R&D and scientific groups. It is worth noting that the departments included in this cluster are characterised by the presence of a number of Indigenous and Afro-Colombian communities, with potential to capitalise on traditional and ancestral knowledge. Finally, Cluster 4 groups the northern Amazon departments and is characterised by high multidimensional poverty, low logistical development, low economic diversification, and low diffusion of R&D and scientific groups. However, this cluster also encompasses protected areas, pristine forest ecosystems and agricultural exclusion zones which contain significant stocks of primary biomass and genetic resources. Moreover, it has the highest government public expenditure, which on the one hand highlights the debt pressure and the wider economic and social isolation of these departments, but on the other hints at the potential to channel large resources into targeted BE activities.

4.2. *Regional analysis: local features*

Given that Colombia is a mega-diverse country, the lack of consideration of specific characteristics at lower-level geographical scales could inhibit the success and effectiveness of BE development and could result in adverse unintended effects. The asset endowment check in Section 4.1 provides a baseline macro-level multi-dimensional assessment of the sustainability dimensions which can help initial targeting of BE strategies through the identification of macro-clusters. For a more granular analysis of local conditions, here we adopt the approach in Pulselli et al. (2015). The proposed synthesis tool is represented by a three-axis diagram (a cube), where the axes represent the economic, social and environmental dimensions. For each dimension, the same indicator variables employed in the asset check (Table 2) are normalised on the 0–1 interval and their arithmetic mean is used as a synthesis index summarising sustainability-related characteristics of BE strategies.[4] In other words, for each department we obtain one value for each sustainability dimension (economic, social and environmental) summarising its BE enabling endowment potential. The higher the index value, the higher is the department endowment on the corresponding dimension. Plotting the indexes on the relevant axis allows us to allocate each Colombian department to a sector of the cube. Each department is now therefore described by its endowment status, revealing that within the same region remarkable differences exist. Fig. 5 shows an example for departments located in four Colombian regions specifically considered in this application and allows a more nuanced interpretation of their BE potential.

For example, considering the departments in the Orinoco region which were grouped in the same macro-cluster (Arauca, Casanare, Meta, see Fig. 4), it is possible to note how the social endowment in Arauca (cube I) is actually lower than in Casanare and Meta (cube II). Similarly, considering the three departments of the Coffee Zone which are grouped in the same macro-cluster (Caldas, Risaralda, Quindío, see Fig. 4), Caldas (cube III) actually exhibits a lower environmental endowment than Risaralda and Quindío (cube IV) even though it has a similar economic and social endowment. This analysis, therefore, equips decision makers with the information necessary to further fine-tune BE strategies either by adapting macro-level pathways to specific departmental requirements or, conversely, by monitoring local BE impacts to steer specific department-level BE schemes closer towards their macro-cluster pathway.[5]

4.3. Trade-off analysis: stakeholder values

The social dimension of BE investments is explored in the trade-off analysis (Fig. 3) where priorities and expectations identified at the strategic/regional level need to match local stakeholders' views. Local private and public operators and civil society, who have the local knowledge of the region, should actively participate in the BE investments decisions to avoid conflicts.

In this case study, we develop a consultation survey and a regional workshop to actively consult the stakeholders' expectations on BE projects. Key stakeholders, who operate or intend to operate in different BE sectors in the four regions, are identified and consulted. Table 1 represents the initial list of sectors to focus on and, through a mix-method approach which involves analysis of firms' register, consultation with local representatives and snowball contacts (for details see Ferrini et al., 2021), a list of stakeholders was compiled and they were invited to participate in a workshop and online consultation survey. A total of 167 stakeholders contributed to the final consultation.[6] Table 3 synthetises the involvement of stakeholders by BE sectors.

From Tables 3 and it emerges that a number of sectors are well represented in our sample such as biodiversity, agriculture and bioenergy. However, stakeholders in some sectors (bio-intelligence and silviculture) are not well captured. Stakeholders were asked to prioritise the leading sectors for their region and Table 4 reports the resulting rankings. R&D activities were given top priority by stakeholders operating in Valle del Cauca, Antioquia and the Coffee Zone. On the other hand, the majority of stakeholders in the Orinoquía region thought that sectors related to biodiversity and ecosystem services, such as nature-based tourism, carbon sequestration and storage, and bioprospecting should be prioritised. Sectors related to agricultural and livestock activities, such as agroforestry, precision farming, pasture intensification, were considered important in Valle del Causa and the Orinoquía, two regions with extensive agropastoral activities. Generally, while stakeholders' rankings in Valle del Cauca and Antioquia seem to adhere to a more bio-technological and bio-resource vision of BE development, stakeholders in the Orinoquía and the Coffee Zone appear supporting bio-based sectors encompassed in the bio-ecological vision.

Stakeholders also shared their vision about the most important BE enabling factors, categorised in economic, social and environmental. Fig. 6 reports the importance of economic enabling factors. The existence of "bioeconomy value chains" at the regional level is, unsurprisingly, the most important factor in all regions. Efficient public governance, good R&D and IT infrastructures are also generally relevant whereas different views emerge for soft credits, market incentives and public infrastructure. Private banking services are not considered strategic for BE initiatives.

The social enabling factors and their scoring are in Fig. 7. The presence of universities and research centres is a capital endowment priority in all the four regions. Entrepreneurial culture, creativity, trust and cooperation, and public acceptance are other crucial factors to support BE initiatives. Interestingly, access to education is considered more important by stakeholders in the Orinoquía, while social security, low inequality and poverty, and ancestral knowledge do not seem to be significant enabling factors as far as this stakeholders sample was concerned.

Environmental enabling factors are in Fig. 8 and biodiversity and protected areas appear to be the most important features. Efficient land use is also rated highly, however only agricultural land was unanimously considered a key factor. This finding might point to tension at the local level between protected areas, biodiversity protection and the use of land for agricultural purposes, echoing findings in Johnson et al. (2022b). Finally, biomass availability seems to be more relevant to stakeholders in Antioquia and Valle del Cauca than to those in the Orinoquía and the Coffee Zone region.

Overall, the findings of the social consultation signal a heterogeneity of needs and views that should lead to adequate planning of BE projects.

5. Discussion

Bioeconomy represents a policy strategy which has attracted interest from a diverse range of stakeholders in the public and private sphere based on its potential to attain a resource-efficient and low-emission development path. If framed within the principles of an extended circular economy framework, BE can represent a powerful paradigm for the transition to a more equitable, sustainable, value-added and knowledge-based growth. At the same time, the wide variety of productive sectors, contextual factors, drivers, and implications involved in possible BE pathways increases the need for more effective and integrated policy decision-making down to the regional-local level. Our stakeholders' consultation reports the existence of different views and the possibility of unintended adverse consequences if initiatives are not comprehensively and coherently planned. If BE initiatives are not correctly planned, they can lead to inefficient allocation of resources, competition for natural resources, over-exploitation, land use pressures, and deterioration of the social relationships. Huddart et al. (2022) emphasise the necessity for extensive collaboration opportunities, advocating for scientists and government representatives to join forces in supporting a data-driven BE pathway especially for mega-diverse countries like Colombia. Therefore, a BE decision support procedure is necessary to guide decision makers' choices from macro-level ambitions to local views and needs. The feasibility of our decision support

[4] The arithmetic mean is preferred to a weighted mean approach in order to obtain a neutral synthesis index, considering the uncertainty about the weights that the different enabling endowments have in determining bioeconomy development pathways.

[5] Although Fig. 5 reports just a few departments, the characterization of all Colombian departments is in the Supplementary Materials.

[6] Of the stakeholders contributing to the consultation, 39 were active in Valle del Cauca, 52 in the Orinoquía, 43 in the Coffee Zone, 42 in Antioquia and 58 in more than one or other regions.

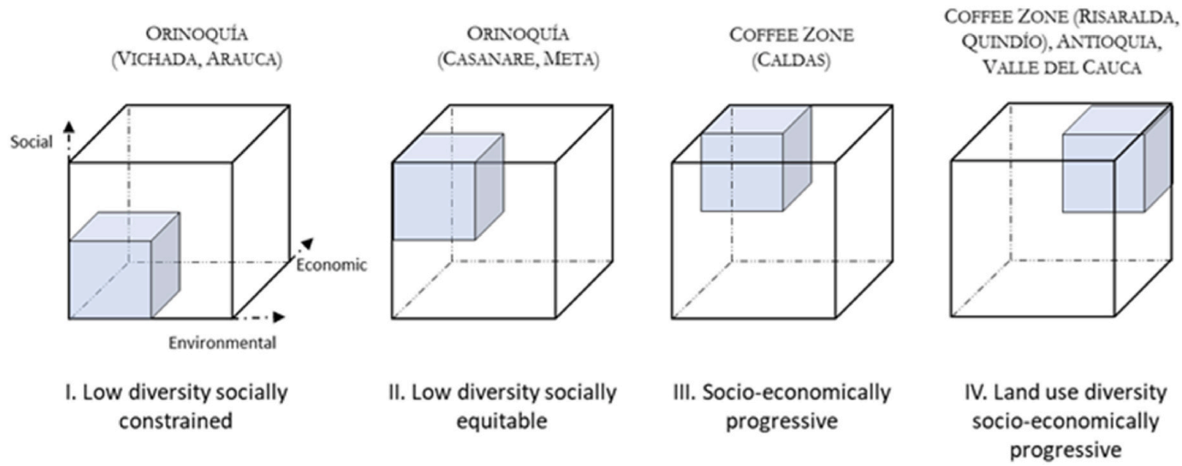

Fig. 5. Department level endowment pathways on the three-dimensional sustainability axes.

Table 3
Stakeholders' involvement in bioeconomy sectors.

Sector	Antioquia	Coffee Zone	Orinoquía	Valle del Cauca	All regions
Biodiversity	38.0%	37.2%	59.6%	46.2%	46.7%
Agriculture	40.5%	44.2%	55.7%	56.4%	41.3%
Ecological engineering	21.5%	27.9%	23.0%	20.5%	29.9%
Green Chemistry	23.8%	32.5%	15.4%	30.8%	20.4%
Bioenergy	16.7%	16.2%	15.4%	15.4%	19.8%
Food and Beverages	11.9%	16.2%	25.0%	23.1%	16.8%
Medicine and Human health	16.7%	20.9%	5.8%	7.7%	14.4%
Silviculture	7.2%	9.2%	11.5%	5.2%	6.0%
Bio-intelligence	7.1%	6.9%	0.0%	10.3%	4.2%
Other	19.1%	16.2%	9.6%	17.9%	18.0%

Table 4
Stakeholder views on the bioeconomy sectors to prioritise by region.

Rank	Valle del Cauca	Antioquia	Orinoquía	Coffee Zone
First	Bioresearch and development	Bioresearch and development	Biodiversity and Ecosystem services	Bioresearch and development
Second	Green Chemistry and Biotechnology	Medicine and Human health	Agriculture and Livestock Industry	Ecological Engineering
Third	Agriculture and Livestock Industry	Biodiversity and Ecosystem services	Bioenergy	Biodiversity and Ecosystem services

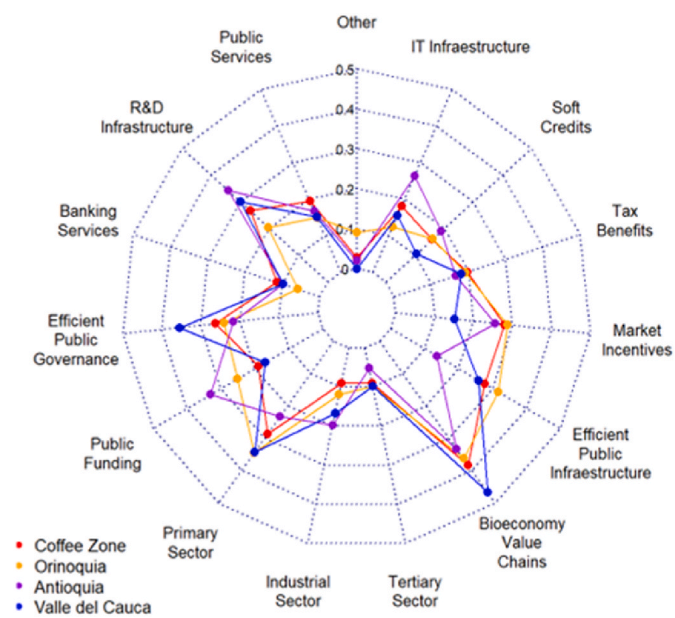

Fig. 6. Stakeholder views on bioeconomy economic enabling factors.

procedure is tested in four Colombian regions contributing to the bioeconomic literature for Latin America which either focuses on specific regions/bioeconomy sectors (Alviar et al., 2021; Solarte-Toro et al., 2023) or on stakeholders' views (Aparicio, 2022; Johnson et al., 2022a). The BE-BSA, applied to the Colombian case study, sets a number of organised and replicable steps (along with analysis tools) to support the implementation of BE initiatives. Our decision support procedure integrates information into comprehensive evidence levels, informing the full policy cycle of BE policy. The strategic analysis which rely on national indicators consents to identify similarities and prospective sectors, the regional analysis unfolds local assets, requirements and impacts, and participatory methods capture stakeholders' views in the trade-off analysis.

Our analysis unveiled insights into the different levels of BE governance and implementation which need to be considered for a successful bio-based development in the country. At the macro strategic level, the Colombian government seems to mainly embrace a bio-technological vision with elements of a bio-resource vision. The asset check, undertaken through the cluster analysis, supports the macro-strategic vision for some of the country's subregions which are endowed with suitable infrastructures and socio-economic capital, namely the central Andean region and the contiguous departments, with potential to foster spillovers in nearby clusters (clusters 1 and 2, Fig. 4). However, for other macro-clusters where high biodiversity and ecosystem resources exist, such as the Amazon region and the departments of Chocó and La Guajira (clusters 3 and 4, Fig. 4), the bio-technological switch is less desirable and bounded by the lack of technological and infrastructural facilities. Alviar et al. (2021) reports a similar divide and high diversity across regions.

Drilling down into the local level context, at the single department level in the regional analysis, a visual synthesis of indexes in the three-dimensional plot (the cubes in Fig. 5) classifies the asset endowments into eight possible configurations of high-low combinations over the sustainability dimensions (economic, social, environmental). For example, considering the departments in the Orinoquía region that are grouped in the same cluster (Arauca, Casanare, Meta, see Fig. 4), we report differences in the social capital endowment which should be

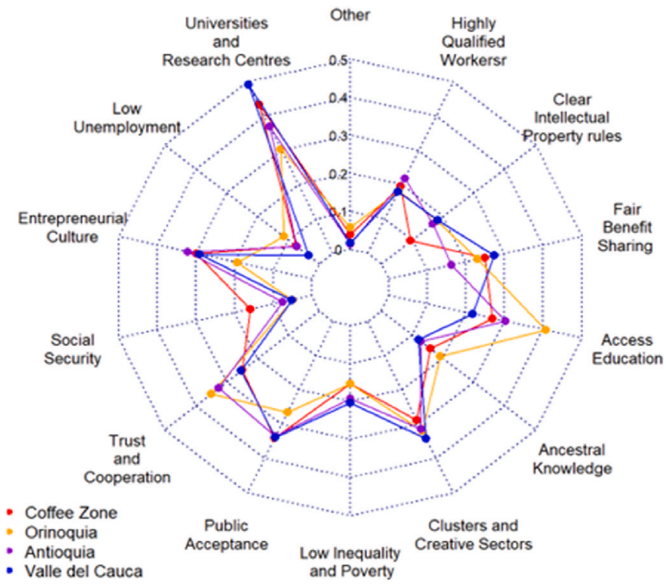

Fig. 7. Stakeholder views on bioeconomy social enabling factors.

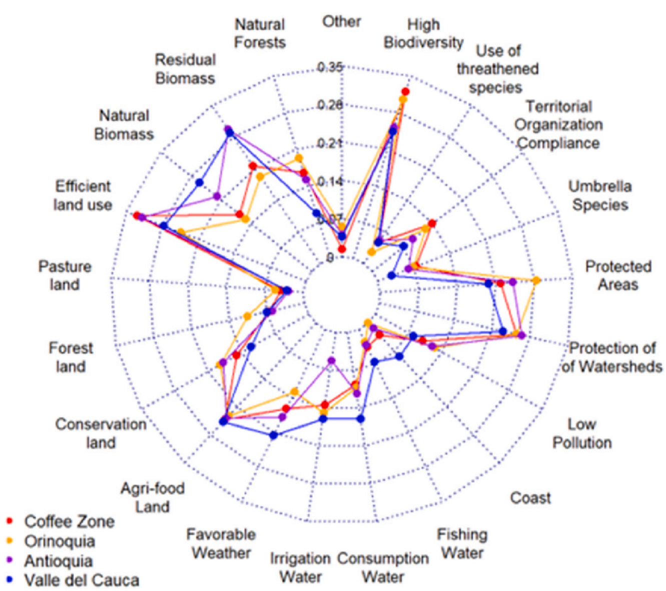

Fig. 8. Stakeholder views on bioeconomy environmental enabling factors.

taken into consideration when developing BE pathways targeting this macro-cluster. In addition, once a decision support procedure such as the BSA is adopted, the regional analysis step can act as a monitoring and assessment tool for the local impact of BE implementations over time. In other words, the policy use can be twofold. On the one hand, it can inform the fine-tuning of macro-cluster strategies down to local level; on the other hand, decision makers can monitor BE impacts steering the local pathway closer to the macro-cluster pathway in order to implement a cluster-coherent strategy.

6. Recommendations for Colombia

In the future, there are both opportunities and challenges for the further development of BE in Colombia. Within the wider national strategy, the country requires the development of regional and local transition roadmaps accounting for and harnessing the heterogeneity of its landscape and culture, including local communities and stakeholders as key actors in this transition. Key to the success of such a transition are expanded knowledge hubs and truly participatory networks. These networks must bring together collaborating entities which encompass private businesses, financial organizations, NGOs, government (local to national) and local communities and indigenous groups. Sustainable BE investments and their implementation will depend on both local push and a sub-national/national pull, enabled through appropriate financial mechanisms. For some of the macro-clusters identified, a stronger focus on environmental sustainability should be incorporated in the local roadmaps given the rich biological capital and to avoid unintended environmental degradation. Similarly, some areas are lagging in terms of the infrastructural requirements for a bio-technological vision with the risk of perpetuating regional inequalities in the absence of a targeted BE plan. Overall, the rate of transition to a more BE-based development path in Colombia needs to be both 'measured incremental change', taking full advantage of the evidence base anchored to a comprehensive capital asset check and stakeholder preferences, and regionally diversified, building on in situ regional to local natural resource and cultural endowments. This balanced transition needs to rely on assessment and monitoring procedures and tools, such as the BE-BSA, that are standardised and replicable and that can coherently complement SDGs indicators, national accounts and natural capital accounts approaches such as the System of Environmental Economic Accounting.

7. Conclusions

While the BE concept has been extensively debated from a theoretical perspective and a number of assessment and monitoring tools have been proposed for specific value chains or continents, this paper supports a circular BE transition that is practical, feasible, and efficient to the country's scale requirements and is driven by empirical local evidence. The strength of the decision support procedure presented is the organisation of indicators, evidence and views into sequential piece of information which helps to map conflicts between national level ambitions and stakeholders' views. We claim that the stakeholders' involvement is key to the success of a BE transition, especially in countries like Colombia where a rapid switch to BE initiatives can compromise social inclusion and development. The stakeholders' values and trade-offs analysis helps to understand whether local stakeholders' expectations and needs match the strategic and endowment considerations identified. For example, if a strategic national BE ambition aims to promote a bio-technological vision but stakeholders prioritise a bio-based and bio-ecological vision, challenges can emerge. Educational and capacity building programmes as well as public cooperation opportunities should be established before BE activities can thrive and enhance the social and economic conditions at the regional and national scale.

While standardised and replicable assessment and monitoring procedures such as the BE-BSA are needed to guide a sustainable bioeconomy transition, our application to the Colombian case study highlights some limitations and future directions. First, the headline indicator variables in the strategic analysis are inevitably a subset of the possible indicators measuring the BE transition. In the absence of a widely agreed set of indicators for the BE, our choice was constrained by the need to keep a manageable number using existing data. Going forward, a set of standardised indicators will need to be identified by the BE stakeholders to allow for enhanced comparability and consistency, for example using the SGDs indicators as a guiding framework. Second, the BA-BSA flexibility allows to deploy the most appropriate tools depending on the specific case study. In this application, cluster analysis, synthesis tool, and consultation survey and workshops were deployed. However, additional tools could provide a more nuanced picture of the BE strategies, for example extended cost-benefit analyses including ecosystem services values. Third, the BE-BSA can be a data and time intensive approach in the short-term but once the procedure is systematically employed, it results in a valuable monitoring tool. Finally, while the BE-BSA is scalable and transferable, applications in other countries and contexts could shed light on its wider use and its complementarity with national accounts, natural capital accounts and the SDGs framework.

CRediT authorship contribution statement

Gaetano Grilli: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Tatiana Cantillo:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Kerry Turner:** Conceptualization, Funding acquisition, Methodology, Writing - original draft, Writing - review & editing. **Jaime Erazo:** Conceptualization, Data curation, Investigation, Writing - review & editing. **Mario Andrés Murcia López:** Writing - review & editing. **Juan Sebastian Valle Parra:** Writing - review & editing. **Felipe Garcia Cardona:** Writing - review & editing. **Silvia Ferrini:** Conceptualization, Funding acquisition, Methodology, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.120042.

References

Aguilar, A., Twardowski, T., Wohlgemuth, R., 2019. Bioeconomy for sustainable development. Biotechnol. J. 14, 1800638 https://doi.org/10.1002/biot.201800638.

Alviar, M., García-Suaza, A., Ramírez-Gómez, L., Villegas-Velásquez, S., 2021. Measuring the contribution of the bioeconomy: the case of Colombia and Antioquia. Sustainability 13 (4), 2353.

Aparicio, A., 2022. The road ahead: narratives and imaginaries of the value of biodiversity in shaping bioeconomy policy in Colombia. Tapuya: Latin American Science, Technology and Society 5 (1), 2059137.

Bartholomew, D.J., Steele, F., Moustaki, I., Galbraith, J.I., 2008. Analysis of Multivariate Social Science Data, second ed. Chapman & Hall-CRC, Boca Raton.

Biber-Freudenberger, L., Basukala, A.K., Bruckner, M., Börner, J., 2018. Sustainability performance of national bio-economies. Sustainability 10 (8), 2705. https://doi.org/10.3390/su10082705.

Bortoloto Damasceno Barcelos, S.M., Salvador, R., Vetroni Barros, M., Carlos de Francisco, A., Guedes, G., 2021. Circularity of Brazilian silk: promoting a circular bioeconomy in the production of silk cocoons. J. Environ. Manag. 296, 113373 https://doi.org/10.1016/j.jenvman.2021.113373.

Bracco, S., Tani, A., Çalıcıoğlu, Ö., Gomez San Juan, M., Bogdanski, A., 2019. Indicators to Monitor and Evaluate the Sustainability of Bioeconomy. Overview and a Proposed Way Forward. FAO, Rome.

Bröring, S., Laibach, N., Wustmans, M., 2020. Innovation types in the bioeconomy. J. Clean. Prod. 266, 121939 https://doi.org/10.1016/j.jclepro.2020.121939.

Bugge, M.M., Hansen, T., Klitkou, A., 2016. What is the bioeconomy? A review of the literature. Sustainability 8 (7), 691. https://doi.org/10.3390/su8070691.

D'Adamo, I., Falcone, P.M., Morone, P., 2020. A new socio-economic indicator to measure the performance of bioeconomy sectors in Europe. Ecol. Econ. 176, 106724 https://doi.org/10.1016/j.ecolecon.2020.106724.

D'Amato, D., Korhonen, J., 2021. Integrating the green economy, circular economy and bioeconomy in a strategic sustainability framework. Ecol. Econ. 188, 1074143 https://doi.org/10.1016/j.ecolecon.2021.107143.

Daly, H.E., 1973. Economics, Ecology. Ethics. Freeman, San Francisco.

DANE Departamento Administrativo Nacional de Estadística, 2016. Producto interno bruto por departamento. www.dane.gov.co/index.php/estadisticas-por-tema/cuentas-nacionales/cuentas-nacionales-departamentales.

DANE Departamento Administrativo Nacional de Estadística, 2018a. Cobertura de Internet (Censo). www.terridata.dnp.gov.co.

DANE Departamento Administrativo Nacional de Estadística, 2018b. Indice de Pobreza Multidimensional. www.microdatos.dane.gov.co.

Devaney, L., Iles, A., 2019. Scales of progress, power and potential in the US bioeconomy. J. Clean. Prod. 233, 379–389. https://doi.org/10.1016/j.jclepro.2019.05.393.

Dieken, S., Dallendörfer, M., Henseleit, M., Siekmann, F., Venghaus, S., 2021. The multitudes of bioeconomies: a systematic review of stakeholders' bioeconomy perceptions. Sustain. Prod. Consum. 27, 1703–1717. https://doi.org/10.1016/j.spc.2021.04.006.

Dietz, T., Börner, J., Förster, J.J., Von Braun, J., 2018. Governance of the bioeconomy: a global comparative study of national bioeconomy strategies. Sustainability 10 (9), 3190. https://doi.org/10.3390/su10093190.

DNP, 2020. Bioeconomia para Colombia. https://www.dnp.gov.co/Crecimiento-Verde/Documents/Comite%20Sostenibilidad/Presentaciones/Sesi%C3%B3n%2011/3_Balance_resultados_2020_estrategia_misi%C3%B3n_bioeconom%C3%ADa_retos_2021.pdf.

Donner, M., Erraach, Y., López-i-Gelats, F., Manuel-i-Martin, J., Yatribi, T., Radić, I., El Hadad-Gauthier, F., 2022. Circular bioeconomy for olive oil waste and by-product valorisation: actors' strategies and conditions in the Mediterranean area. J. Environ. Manag. 321, 115836 https://doi.org/10.1016/j.jenvman.2022.115836.

Drupp, M.A., Meya, J.N., Baumgärtner, S., Quaas, M.F., 2018. Economic inequality and the value of nature. Ecol. Econ. 150, 340–345. https://doi.org/10.1016/j.ecolecon.2018.03.029.

El-Chichakli, B., von Braun, J., Lang, C., Barben, D., Philp, J., 2016. Policy: five cornerstones of a global bioeconomy. Nature 535, 221–223. https://doi.org/10.1038/535221a.

European Commission, 2018. A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment. Publications Office of the European Union, Luxembourg. https://doi.org/10.2777/478385.

Everitt, B.S., Landau, S., Leese, M., Stahl, D., 2011. Cluster Analysis, fifth ed. John Wiley & Sons, Chichester.

Ferrini, S., Grilli, G., Cantillo, T., Turner, K., Erazo, J., Di Maria, C., Murcia López, M.A., Valle Parra, J.S., García Cardona, F., Flechas, S.V., Valderrama, N., Azcárate, J., Restrepo, S., Di Palma, F., 2021. Bioeconomy Opportunities for Four Colombian Regions. Bogotá, Colombia https://doi.org/10.6084/m9.figshare.16755409.

González-Castaño, M., Hani Kour, M., González-Arias, J., Baena-Moreno, F.M., Arellano-Garcia, H., 2021. Promoting bioeconomy routes: from food waste to green biomethane. A profitability analysis based on a real case study in eastern Germany. J. Environ. Manag. 300, 113788 https://doi.org/10.1016/j.jenvman.2021.113788.

Haarich, S., 2017. Bioeconomy Development in EU Regions: Mapping of EU Member States'/regions' Research and Innovation Plans & Strategies for Smart Specialisation (RIS3) on Bioeconomy. Publications Office of the European Union, Luxembourg.

Hansen, T., 2022. The foundational economy and regional development. Reg. Stud. 56 (6), 1033–1042. https://doi.org/10.1080/00343404.2021.1939860.

Heimann, T., 2019. Bioeconomy and SDGs: does the bioeconomy support the achievement of the SDGs? Earth's Future 7 (1), 43–57.

Hernández, V.L., Schanz, H., 2019. Agency in actor networks: who is governing transitions towards a bioeconomy? The case of Colombia. J. Clean. Prod. 225, 728–742. https://doi.org/10.1016/j.jclepro.2019.03.306.

Hinderer, S., Brändle, L., Kuckertz, A., 2021. Transition to a sustainable bioeconomy. Sustainability 13 (15), 8232. https://doi.org/10.3390/su13158232.

Hirsch, F., 1976. Social Limits to Growth. Harvard University Press.

Huddart, J.E., Crawford, A.J., Luna-Tapia, A.L., Restrepo, S., Di Palma, F., 2022. EBP-Colombia and the bioeconomy: genomics in the service of biodiversity conservation and sustainable development. Proc. Natl. Acad. Sci. USA 119 (4), e2115641119.

IDEAM Instituto de Hidrología, 2014. Meteorología y estudios ambientales. In: Mapa de Coberturas de la Tierra Metodología CORINE Land Cover 2010-2012. www.siac.gov.co/catalogo-de-mapas.

IGAC Instituto Geográfico Agustín Codazzi, 2014. Base de datos vectorial básica. Colombia. www.geoportal.igac.gov.co/contenido/datos-abiertos-cartografia-y-geografia.

Ingrao, C., Bacenetti, J., Bezama, A., Blok, V., Geldermann, J., Goglio, P., Koukios, E., Lindner, M., Nemecek, T., Siracusa, V., Zabaniotou, A., Huisingh, D., 2016. Agricultural and forest biomass for food, materials and energy: bio-economy as the cornerstone to cleaner production and more sustainable consumption patterns for accelerating the transition towards equitable, sustainable, post fossil-carbon societies. J. Clean. Prod. 117, 4–6. https://doi.org/10.1016/j.jclepro.2015.12.066.

Johnson, F.X., Canales, N., Fielding, M., Gladkykh, G., Aung, M.T., Bailis, R., et al., 2022a. A comparative analysis of bioeconomy visions and pathways based on stakeholder dialogues in Colombia, Rwanda, Sweden, and Thailand. J. Environ. Pol. Plann. 24 (6), 680–700.

Johnson, F.X., Canales, N., Fielding, M., Gladkykh, G., Aung, M.T., Bailis, R., Ogeya, M., Olsson, O., 2022b. A comparative analysis of bioeconomy visions and pathways

based on stakeholder dialogues in Colombia, Rwanda, Sweden, and Thailand. J. Environ. Pol. Plann. https://doi.org/10.1080/1523908X.2022.2037412.
Kardung, M., Cingiz, K., Costenoble, O., Delahaye, R., Heijman, W., Lovrić, M., van Leeuwen, M., M'Barek, R., van Meijl, H., Piotrowski, S., Ronzon, T., Sauer, J., Verhoog, D., Verkerk, P.J., Vrachioli, M., Wesseler, J.H.H., Zhu, B.X., 2021. Development of the circular bioeconomy: drivers and indicators. Sustainability 13 (1), 413. https://doi.org/10.3390/su13010413.
Kardung, M., Drabik, D., 2021. Full speed ahead or floating around? Dynamics of selected circular bioeconomies in Europe. Ecol. Econ. 188, 107146 https://doi.org/10.1016/j.ecolecon.2021.107146.
Kaufman, L., Rousseeuw, P.J., 1990. Finding Groups in Data: an Introduction to Cluster Analysis. Wiley, New York.
Kershaw, E.H., Hartley, S., McLeod, C., Polson, P., 2021. The sustainable path to a circular bioeconomy. Trends Biotechnol. 39 (5), 542–544. https://doi.org/10.1016/j.tibtech.2020.10.015.
Kircher, M., Breves, R., Taden, A., Herzberg, D., 2018. How to capture the bioeconomy's industrial and regional potential through professional cluster management. N. Biotech. 40, 119–128. https://doi.org/10.1016/j.nbt.2017.05.007.
Kircher, M., 2021. The framework conditions must be aligned to the requirements of the bioeconomy. EFB Bioeconomy Journal 1, 100003. https://doi.org/10.1016/j.bioeco.2021.100003.
Laibach, N., Börner, J., Bröring, S., 2019. Exploring the future of the bioeconomy: an expert-based scoping study examining key enabling technology fields with potential to foster the transition toward a bio-based economy. Technol. Soc. 58, 101118 https://doi.org/10.1016/j.techsoc.2019.03.001.
Luhas, J., Mikkilä, M., Kylkilahti, E., Miettinen, J., Malkamäki, A., Pätäri, S., Korhonen, J., Pekkanen, T., Tuppura, A., Lähtinen, K., Autio, M., Linnanen, L., Ollikainen, M., Toppinen, A., 2021. Pathways to a forest-based bioeconomy in 2060 within policy targets on climate change mitigation and biodiversity protection. For. Pol. Econ. 131, 102551 https://doi.org/10.1016/j.forpol.2021.102551.
McGlade, J., Palahi, M., Costanza, R., Kubiszewski, I., Trebeck, K., Fiaromonti, L., Lovins, H., Wallis, S., Pickett, K., Wilkinson, R., 2020. Investing in nature to transform the post COVID-19 economy: a 10-point action plan to create a circular bioeconomy devoted to sustainable wellbeing. The Solutions Journal 11 (2).
Meyer, R., 2017. Bioeconomy strategies: contexts, visions, guiding implementation principles and resulting debates. Sustainability 9, 1031. https://doi.org/10.3390/su9061031.
Minagricultura, 2019. Unidad de Planificación rural agropecuaria. Identificación general de la frontera agrícola en Colombia. www.sipra.upra.gov.co.
Minciencias, 2019. Grupos de Investigación reconocidos 2019. www.datos.gov.co/Ciencia-Tecnolog-a-e-Innovaci-n/Grupos-de-Investigaci-n-reconocidos-2019.
Minciencias, 2020. Bioeconomía para una Colombia Potencia viva y diversa. Bogotá, D. C.
Minhacienda, 2018. Informe de Viabilidad Fiscal Territorial 2018. www.minhacienda.gov.co/webcenter/portal/Estadisticas.
Mishan, E.J., 1978. The Costs of Economic Growth. Praeger, New York.
Morone, P., 2018. Sustainability transition towards a biobased economy: defining, measuring and assessing. Sustainability 10 (8), 2631. https://doi.org/10.3390/su10082631.
Mougenot, B., Doussoulin, J., 2022. Conceptual evolution of the bioeconomy: a bibliometric analysis. Environ. Dev. Sustain. 24, 1031–1047. https://doi.org/10.1007/s10668-021-01481-2.
Muscat, A., de Olde, E.M., Kovacic, Z., de Boer, I.J.M., Ripoll-Bosch, R., 2021. Food, energy or biomaterials? Policy coherence across agro-food and bioeconomy policy domains in the EU. Environ. Sci. Pol. 123, 21–30. https://doi.org/10.1016/j.envsci.2021.05.001.
Niang, A., Torre, A., Bourdin, S., 2022. How do local actors coordinate to implement a successful biogas project? Environ. Sci. Pol. 136, 337–347. https://doi.org/10.1016/j.envsci.2022.06.019.
O'Brien, M., Wechsler, D., Bringezu, S., Schaldach, R., 2017. Toward a systemic monitoring of the European bioeconomy: gaps, needs and the integration of sustainability indicators and targets for global land use. Land Use Pol. 66, 162–171. https://doi.org/10.1016/j.landusepol.2017.04.047.
PNN Parques Nacionales Naturales de Colombia, 2019. áreas protegidas registradas en el registro único de áreas protegidas. www.datos.gov.co/Ambiente-y-Desarrollo-Sostenible/Rest-Mapservice/ckeb-w99r.
Priefer, C., Jörissen, J., Frör, O., 2017. Pathways to shape the bioeconomy. Resources 6 (1), 10. https://doi.org/10.3390/resources6010010.
Pulselli, F.M., Coscieme, L., Neri, L., Regoli, A., Sutton, P.C., Lemmi, A., Bastianoni, S., 2015. The world economy in a cube: a more rational structural representation of sustainability. Global Environ. Change 35, 41–51. https://doi.org/10.1016/j.gloenvcha.2015.08.002.
Raworth, K., 2017. Why it's time for Doughnut Economics. Progressive Review 24 (3), 216–222.
Robert, N., Giuntoli, J., Araujo, R., Avraamides, M., Balzi, E., Barredo, J.I., Baruth, B., Becker, W., Borzacchiello, M.T., Bulgheroni, C., Camia, A., Fiore, G., Follador, M., Gurria, P., la Notte, A., Lusser, M., Marelli, L., M'Barek, R., Parisi, C., Philippidis, G., Ronzon, T., Sala, S., Sanchez Lopez, J., Mubareka, S., 2020. Development of a bioeconomy monitoring framework for the European Union: an integrative and collaborative approach. N. Biotech. 59, 10–19. https://doi.org/10.1016/j.nbt.2020.06.001.
Rockström, J., Steffen, W., Noone, K., et al., 2009. A safe operating space for humanity. Nature 461, 472–475. https://doi.org/10.1038/461472a.
Rojas-Jimenez, H.H., 2021. Local economic development and the Colombian strategy for a sustainable and inclusive bioeconomy. Science, Technology, and Higher Education: Governance Approaches on Social Inclusion and Sustainability in Latin America 115–150.
Ronzon, T., M'Barek, R., 2018. Socioeconomic indicators to monitor the EU's bioeconomy in transition. Sustainability 10 (6). https://doi.org/10.3390/su10061745, 2018.
Ronzon, T., Sanjuán, A., 2020. Friends or foes? A compatibility assessment of bioeconomy-related Sustainable Development Goals for European policy coherence. J. Clean. Prod. 254, 119832 https://doi.org/10.1016/j.jclepro.2019.119832.
Salvador, R., Puglieri, F.N., Halog, A., de Andrade, F.G., Piekarski, C.M., De Francisco, A. C., 2021. Key aspects for designing business models for a circular bioeconomy. J. Clean. Prod. 278, 124341 https://doi.org/10.1016/j.jclepro.2020.124341.
Sanz-Hernández, A., Sanagustín-Fons, M.V., López-Rodríguez, M.E., 2019. A transition to an innovative and inclusive bioeconomy in Aragon, Spain. Environ. Innov. Soc. Transit. 33, 301–316. https://doi.org/10.1016/j.eist.2019.08.003.
Sasson, A., Malpica, C., 2018. Bioeconomy in Latin America. New biotechnology 40, 40–45. https://doi.org/10.1016/j.nbt.2017.07.007.
Schaafsma, M., Eigenbrod, F., Gasparatos, A., Gross-Camp, N., Hutton, C., Nunan, F., Schreckenberg, K., Turner, K., 2021. Trade-off decisions in ecosystem management for poverty alleviation. Ecol. Econ. 187, 107103 https://doi.org/10.1016/j.ecolecon.2021.107103.
Scharin, H., Ericsdotter, S., Elliott, M., Turner, K., Niiranen, S., Blenckner, T., Hyytiäinen, K., Ahlvik, L., Ahtiainen, H., Artell, J., Hasselström, L., Söderqvist, T., Rockström, J., 2016. Processes for the sustainable stewardship of marine environments. Ecol. Econ. 128, 55–67. https://doi.org/10.1016/j.ecolecon.2016.04.010.
Solarte-Toro, J.C., Piedrahita-Rodríguez, S., Cardona Alzate, C.A., 2023. A bioeconomy model based on sustainable biorefineries to ensure the sustainable development goals (SDGs) in Colombia. In: A Sustainable Green Future: Perspectives on Energy, Economy, Industry, Cities and Environment. Springer International Publishing, Cham, pp. 139–162.
Staffas, L., Gustavsson, M., McCormick, K., 2013. Strategies and policies for the bioeconomy and bio-based economy: an analysis of official national approaches. Sustainability 5 (6), 2751–2769. https://doi.org/10.3390/su5062751.
Stark, S., Biber-Freudenberger, L., Dietz, T., Escobar, N., Janosch Förster, J., Henderson, J., Laibach, N., Börner, J., 2022. Sustainability implications of transformation pathways for the bioeconomy. Sustain. Prod. Consum. 29, 215–227. https://doi.org/10.1016/j.spc.2021.10.011.
Steffen, W., et al., 2015. Science 347, 1259855. https://doi.org/10.1126/science.1259855.
Stegmann, P., Londo, M., Junginger, M., 2020. The circular bioeconomy: its elements and role in European bioeconomy clusters. Resour. Conserv. Recycl. X 6, 100029. https://doi.org/10.1016/j.rcrx.2019.100029.
Stiglitz, J.E., 2013. The Price of Inequality. Penguin Books, London.
Stiglitz, J.E., Sen, A., Fitoussi, J.P., 2010. Report by the Commission on the Measurement of Economic Performance and Social Progress. Commission on Economic Performance and Social Progress, Paris.
Talberth, J., Weisdorf, M., 2017. Genuine progress indicator 2.0: pilot accounts for the US, Maryland, and city of Baltimore 2012–2014. Ecol. Econ. 142, 1–11. https://doi.org/10.1016/j.ecolecon.2017.06.012.
Turner, K., 2016. The 'balance sheet' approach within adaptive management for ecosystem services. In: Potschin, M., Haines-Young, R., Fish, R., Turner, K. (Eds.), Routledge Handbook of Ecosystem Services. Routledge, London, pp. 289–298.
Turner, K., Badura, T., Ferrini, S., 2019. Natural capital accounting perspectives: a pragmatic way forward. Ecosys. Health Sustain. 5 (1), 237–241. https://doi.org/10.1080/20964129.2019.1682470.
Vivien, F.D., Nieddu, M., Befort, N., Debref, R., Giampietro, M., 2019. The hijacking of the bioeconomy. Ecol. Econ. 159, 189–197. https://doi.org/10.1016/j.ecolecon.2019.01.027.
Wahlund, M., Hansen, T., 2022. Exploring alternative economic pathways: a comparison of foundational economy and Doughnut economics. Sustain. Sci. Pract. Pol. 18 (1), 171–186. https://doi.org/10.1080/15487733.2022.2030280.
Warnecke, T., 2023. Operationalizing the doughnut economy: an institutional perspective. J. Econ. Issues 57 (2), 643–653. https://doi.org/10.1080/00213624.2023.2202570.
WCED, 1987. World commission on environment and development. Our common future 17 (1), 1–91.
Wensing, J., Carraresi, L., Bröring, S., 2019. Do pro-environmental values, beliefs and norms drive farmers' interest in novel practices fostering the Bioeconomy? J. Environ. Manag. 232, 858–867. https://doi.org/10.1016/j.jenvman.2018.11.114.
Wohlfahrt, J., Ferchaud, F., Gabrielle, B., Godard, C., Kurek, B., Loyce, C., Therond, O., 2019. Characteristics of bioeconomy systems and sustainability issues at the territorial scale. A review. J. Clean. Prod. 232, 892–902. https://doi.org/10.1016/j.jclepro.2019.05.385.
Wydra, S., Hüsing, B., Köhler, J., Schwarz, A., Schirrmeister, E., Voglhuber-Slavinsky, A., 2021. Transition to the bioeconomy – analysis and scenarios for selected niches. J. Clean. Prod. 294, 126092 https://doi.org/10.1016/j.jclepro.2021.126092.