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Review

Simulation modelling in bioeconomy: Unraveling trends, gaps, and insights through bibliometric analysis

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ABSTRACT

The bioeconomy, a multidisciplinary approach that utilizes biological resources and processes to produce food, energy, and materials, is crucial for achieving sustainable economic development. As we transition to new value chains and technologies, it is essential to investigate bioeconomic solutions to substitute fossil-based production. Advanced modelling techniques are necessary to address the inherent complexity of bioeconomic systems. This study explores the intersection of simulation modelling and the bioeconomy, highlighting the increasing interest in these methodologies. We identified key trends and research gaps within this domain by conducting a systematic literature review and bibliometric analysis. Our refined search strategy yielded 12 publications focusing on agent-based modelling (ABM) applications in the bioeconomy, providing insights into micro-level and macro-level analyses. The findings reveal ABM's potential to simulate complex interactions within bioeconomic systems, emphasizing its ability to integrate social, economic, and environmental dimensions. The study uncovers gaps in holistically modelling innovative biorefinery technologies. These insights can help guide future research efforts by showing the need for adaptive and interdisciplinary approaches to enhance knowledge about bioeconomic value networks and to derive measures and strategies for their long-term establishment.

1. Introduction

Climate change and its effects are among the most topical issues of our time. Various established and newly developed concepts and innovative technologies are available to counteract negative impacts on ecosystems worldwide. An increasingly researched concept is the bioeconomy. Successfully managed, it may allow for an environmentally, economically and socially sound economy, substituting the fossil economy.

The bioeconomy is a multidisciplinary approach that is intended to act as a driving force towards a more sustainable economy. According to the definition of the European Commission from 2018, 'the bioeconomy covers all sectors and systems that rely on biological resources (animals, plants, micro-organisms, and derived biomass, including organic waste), their functions and principles. It includes and interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries and aquaculture); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services (biomedicines and health biotechnology are excluded).' (EUR-Lex, 2018). The bioeconomy offers technical solutions and promotes (production) strategies to mitigate some of the biggest global challenges, such as food security, climate change, and resource scarcity (Lewandowski, 2018; Sadhukhan et al., 2024).

Literature shows that various modelling approaches are being used to help understand the challenges and opportunities of the transition process towards a bioeconomy. Most studies tackling this situation apply optimisation models to evaluate biomass-based value chains (e.g., Petig et al., 2019; Rudi et al., 2017), while others review the techno-economic performance of innovative bioeconomy concepts (e.g., Götz et al., 2022; Zimmer et al., 2017), but only few apply simulation modelling in the bioeconomy context, such as GLOBIOM (IIASA, 2023), MAGNET (Woltjer et al., 2014) or AgriPoliS (Happe et al., 2006). GLOBIOM (Global Biosphere Management Model) is a global optimisation model that maps land use competition between agriculture, bioenergy, and forestry by representing agriculture, forestry, economic, and demographic indicators (Ilaria et al., 2020). It is used to analyse the effects of indirect land use change (iLUC) and issues like deforestation and crop price changes due to biofuel expansion (Havlík et al., 2011). However, as a partial equilibrium (PE) model, it only covers the agriculture and

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forestry sectors in detail, excluding other sectors (Valin et al., 2016). Another prominent model is the Modular Applied GeNeral Equilibrium Tool, MAGNET. It builds on the Global Trade Analysis Project (GTAP) database to model global economic activity (Sturm and Banse, 2021). It assesses impacts on land use, agricultural trade, biofuels, and food security (Nelson et al., 2014). MAGNET has been further developed to focus on the bioeconomy and the climate-energy-water-food nexus (van Meijl et al., 2018). It helps estimate the economic impacts of policies and technologies, crucial for assessing the sustainability and profitability of the bioeconomy. AgriPoliS (Agricultural Policy Simulator) is an example of an ABM used to simulate the dynamic development of agricultural structures. Its primary purpose is to analyse the influence of policy on structural change in agriculture (Happe et al., 2006).

Besides well established modelling approaches simulation-based modelling is emerging. For instance, Pyka et al. (2022) analyse various approaches to modelling and simulating the bioeconomy. They look at multiple aspects of bioeconomic practices, such as impact factors on climate change or benefits of circular use of biomass. The authors demonstrate that current modelling frameworks can be extended and improved upon. They suggest a cooperative approach that combines established and emerging modelling techniques to address specific research questions. The authors highlight the potential of agent-based models. Stellingwerf et al. (2022) conducted a literature review comparing various logistics and supply chain models for the biobased economy. The authors focused on economic optimisation in this field. Besides Pyka et al. (2022) and Stellingwerf et al. (2022) also Zahraee et al. (2020) show that most modelling studies for the bioeconomy are strategic optimisation models aiming to minimise economic impact.

This paper, however, focuses on simulation modelling, which considers broader system dynamics, social and environmental aspects, going beyond economic optimisation. Simulation modelling can provide a better understanding of the interdependencies, and simulations are essential instruments, especially for political decision-makers, by assessing the cross-sectoral economic, social, and ecological effects of bioeconomy strategies. In particular, they offer the possibility of analysing trends and observing the impact of selected innovations like biorefineries, sustainable agricultural practices and renewable energy technologies (Kolkman, 2020). For instance, Brown et al. (2019) assert that classical models often struggle to incorporate relevant decision processes on various scales, 'from individual to community and government,' (Brown et al., 2019, p. 810) identifying the potential of 'newer' simulation approaches. Pyka and Werker (2009) argue that economists, particularly those engaged with innovations and inherent uncertainty, show interest in the tools provided by simulation models. This is because they are dissatisfied with conventional modelling, which necessitates a very restrictive set of assumptions, especially identical entities making rational decisions, inevitably leading to a deterministic representation of innovation.

There are three different modelling paradigms: System Dynamics, Discrete Event Simulation, and Agent-Based Modelling (Grigoryev, 2023). All three methods have methodological advantages and disadvantages and are particularly suited for different research cases. Discrete-event simulation, although used for modelling supply chains (Brailsford et al., 2014), cannot model continuous changes or trends. Furthermore, it may not fully capture more complex patterns of interaction between actors and potential collective behaviours (Allen, 2011). System dynamics modelling is a frequently used method that enables the visualisation of systemic interactions between socio-economic and ecological systems, considering them as a whole (Pyka et al., 2022). However, it works at a high level of aggregation, making it challenging to map heterogeneous actors and their complex interaction patterns in the bioeconomy (Borshchev and Grigoryev, 2020). Some researchers consider agent-based modelling (ABM) the most promising method for modelling the bioeconomy (Balint et al., 2017; Leibensperger et al., 2021; Schulze et al., 2017).

The bioeconomy involves a multitude of stakeholders whose interactions and decisions have a profound impact on successfully establishing bioeconomic innovations. Examining the intersection between agent-based modelling (ABM) and the bioeconomy is crucial, given the inherent complexity and interconnectedness of the system. ABMs allow for the simulation of these heterogeneous agents and their dynamic interactions, providing insights into how individual behaviours can lead to emergent system-level outcomes. This is valuable for understanding the impacts of policies, market changes, and technological innovations on sustainability goals. ABM seems particularly suitable for analysing the dynamics and processes of technology diffusion of biorefineries (Yang et al., 2022).

Within the bioeconomy, biorefineries form a central unit (Götz et al., 2022; Lewandowski, 2018; Sadhukhan et al., 2024). Sadhukhan et al. (2018) define biorefineries as advanced, multi-process industrial plants that can co-produce a range of bio-based products, including food and pharmaceutical ingredients, fine, speciality and platform chemicals, polymers, biofuels and bioenergy. They also state that biorefineries might have the potential to sustainably balance the triple-bottom-line criteria: environmental, social and economic (Sadhukhan et al., 2018). However, a wide gap between the demonstration of technical feasibility and the commercialization of concepts can be observed (Gírio et al., 2017). Frequently, processes and products would be ready for market introduction, but potential partners and customers cannot be found. Instead, underdeveloped markets and incomplete actor networks can be observed in the bioeconomy (Giurca and Späth, 2017). It can be expected that this problem will become even more challenging in the future as bio-based solutions become more important. Due to the potentially high suitability of simulation modelling approaches, especially ABM, to address current hurdles in bioeconomic transition and the potential key role of biorefineries, ABM and its use case of biorefineries are of particular interest for this study.

Hence, the main goals of this study are to (1) comprehensively review the current state of literature on simulation modelling, in particular on agent-based modelling (ABM) in the bioeconomy, (2) identify current challenges, trends and research gaps, and (3) provide insights that support the development of sustainable bioeconomic practices. By conducting a bibliometric analysis, this study aims to investigate on the potential of ABM in promoting cleaner and more sustainable production.

The present study is structured as follows: Straightforward, we describe the bibliometric analysis, including data collection and definition of search strings; Section 3 illustrates the obtained results and the cluster analysis; Section 4 presents a discussion of the obtained results and proposes a research agenda for future studies; and Section 5 concludes this work.

2. Materials and methods

The present review adopts a mixed approach, combining a bibliometric analysis and a systematic literature review. The bibliometric analysis provides an additional visualisation of existing topic clusters and reveals research priorities. This hybrid approach has been applied across several research fields (Di Letizia et al., 2023; Wang et al., 2022). This literature review aims to provide a comprehensive understanding of simulation modelling in the bioeconomy, focusing on trends and the role of agent-based modelling.

In November 2023, we conducted and analysed a literature search employing the Scopus database. Scopus is central to this work, as it is the scientific database with the most scientific publications in the relevant research field (Singh et al., 2012). To ensure a comprehensive and exhaustive search, we developed three search strings (see Table 1), each progressively refining the search focus, starting with broader search terms and narrowing down to specific aspects.

Table 1 illustrates the diminishing volume of literature resulting from progressively refined thematic search strings. Utilising the formulated search strings, we performed bibliometric analyses, creating three keyword networks. This visualisation of focal points facilitated a

Table 1
Overview of the search strings (status as of November 08, 2023).

Number of search string	Topic	Search terms	Number of publications in Scopus
Search string 1	bioeconomy	"bioeconomy" OR "bio-economy" OR "bio economy"	6569
Search string 2	modelling or simulation of the bioeconomy	("bioeconomy" OR "bio-economy" OR "bio economy") AND ("model*" OR "simulation")	1324
Search string 3	agent-based modelling or simulation of the bioeconomy	("bioeconomy" OR "bio-economy" OR "bio economy") AND ("model*" OR "simulation") AND ("ABM" OR "agent-based model*" OR "agent based model*")	12

more in-depth analysis of the literature. While the substantial amount of literature in search strings 1 and 2 leads to a focused examination of only a portion. Search string 3 entails a thorough analysis of the entire literature. Rigorous inclusion criteria, including language (English), document type (journal article), and publication type (scientific source), are applied to ensure result relevance. Full-text availability is imperative for inclusion. The stringent formulation of the search strings implies that documents not fully aligning with the desired criteria, albeit relevant to the study, may face exclusion from the analysis. To counteract this limitation, we initially conducted a broad search employing a wide range of spellings of the search terms, for example, 'bioeconomy' and 'bio-economy' (see Table 1).

To build networks, we used the software Visualisation Of Similarities viewer (VOSviewer v.1.6.19, Leiden University, 2023). The software generates clusters of nodes representing keywords, with proximity indicating similarity and node size indicating frequency. For an overview of the search parameters employed to generate keyword networks, see Appendix Table A1. The results show the findings from three consecutive search strings, with each string offering a more specific perspective on the literature about modelling and simulation of the bioeconomy.

Although only 12 publications were ultimately identified, this focused selection represents a rigorous filtering process. Each of the 11 publications, for which the full text was available, was thoroughly read and analysed to extract detailed insights. Moreover, we conducted in-depth analyses of entire texts on some of the most cited texts from the initial pool of over 6500 sources, beyond just reviewing titles, keywords, and abstracts. Through the initial analysis of relevant sources, the direction towards focusing on ABM was formed. Additionally, by conducting forward and revearse search, we identified related relevant sources cited by these key publications, which further informed our search strategies. This comprehensive approach, combining a traditional literature review with visual bibliometric analysis, allowed us to obtain a thorough understanding of the multidimensional nature of the bioeconomy, ensuring that the insights derived are both valuable and instructive despite the limited number of final sources. Some other studies have also applied comparable approaches (Di Letizia et al., 2023; Ilaria et al., 2020; Khalid and Singh, 2023). However, these studies have decisive limitations. For instance, Khalid and Singh (2023) limit their analysis to naming clusters without an in-depth exploration of individual publications, and Ilaria et al. (2020) emphasise co-authorship networks for organizations and countries rather than content analysis. In contrast, our work employs a refined and iterative search process to uncover and explore relevant networks, enabling us to delve deeper into the literature on a content level. This advanced method allows us to gain insights that are otherwise overlooked.

3. Results

The results are structured into three sub-chapters, focusing progressively on more specific aspects of the bioeconomy, models, and simulations. This step-by-step approach facilitates comprehensive analysis and scientific discussion. The results are presented by keyword networks, followed by an overview of the number of publications on the respective search string.

3.1. "Bioeconomy" – overview of literature

Some works focus on specific sub-topics of the bioeconomy, such as bioenergy, while others aim to provide guidelines for political decision-makers. The keyword network displayed in Fig. 1 reflects the diversity of subject areas. This great diversity underscores the breadth and interdisciplinary nature of the bioeconomy as a field of research. Simultaneously, it is necessary to refine and specify the search parameters.

Fig. 1 is the keyword network of search string 1. The algorithm structures the 298 terms in five clusters in a contextual grouping. Given that the search string consists of synonyms for 'bioeconomy', this term represents the most prominent node in the network. Numerous nodes are positioned close to 'bioeconomy', highlighting their strong association with the term. These keywords frequently co-occur in the field of bioeconomy.

Notable themes include sustainable development, biorefining, and biomass utilisation. These works highlight the significant interest in bioeconomic practices aimed at sustainability. The network of keywords is derived from 6569 sources obtained via search string 1 in Scopus. The literature search does queries in the title, abstract, and keywords. For example, the study by Dahiya et al. (2018) titled 'Food waste biorefinery: Sustainable strategy for circular bioeconomy' becomes part of the literature body for search string 1 based on its title. However, this work does not include 'bioeconomy' in its keywords. Instead, it features terms such as 'biobased products' or 'bioenergy'. Therefore, the algorithm uses these two terms for the network graph.

Research activities in bioeconomy have increased significantly, as shown in Fig. 2. Despite this trend, bioeconomy remains an emerging field with 1289 publications in 2022, compared to over 48,000 in battery research, indicating that the bioeconomy is still in the early stages of development and a need for further interdisciplinary research.

This bar chart illustrates the growing body of literature in the field of bioeconomy. Imposing no constraints on language or research areas facilitated a comprehensive literature overview. However, the timeframe was confined to the years 2000–2023. The graph reveals that the earliest publication dates back to 2003. Since then, the volume of scientific papers has progressively increased, reaching a peak of 1289 publications in 2022. The decrease in 2023 is attributed to the year still being in progress at the time of this analysis. A forecast for 2023 was obtained by applying an Auto Regressive Integrated Moving Average (ARIMA) forecasting algorithm to previous values. The forecast predicts a significant rise in the number of publications. Fig. 2 illustrates that the bioeconomy has been a research subject in the literature for more than 20 years and has gained significant attention since then. This search string already contains central works on modelling and simulation of the bioeconomy, such as the works of Pyka et al. (2022) or Leibensperger et al. (2021). We have further refined the search string to delve deeper into this aspect.

3.2. 'Bioeconomy', 'Modelling', 'Simulation' – in-depth analysis

The search string was narrowed down in the next step by adding the terms 'modelling' and 'simulation'.

Fig. 3 displays the keyword network for search string 2. The classification in 5 clusters stays the same but containing more terms (433) than before due to the lower threshold value selected agent-based modelling (marking 4) is captured. The central term remains

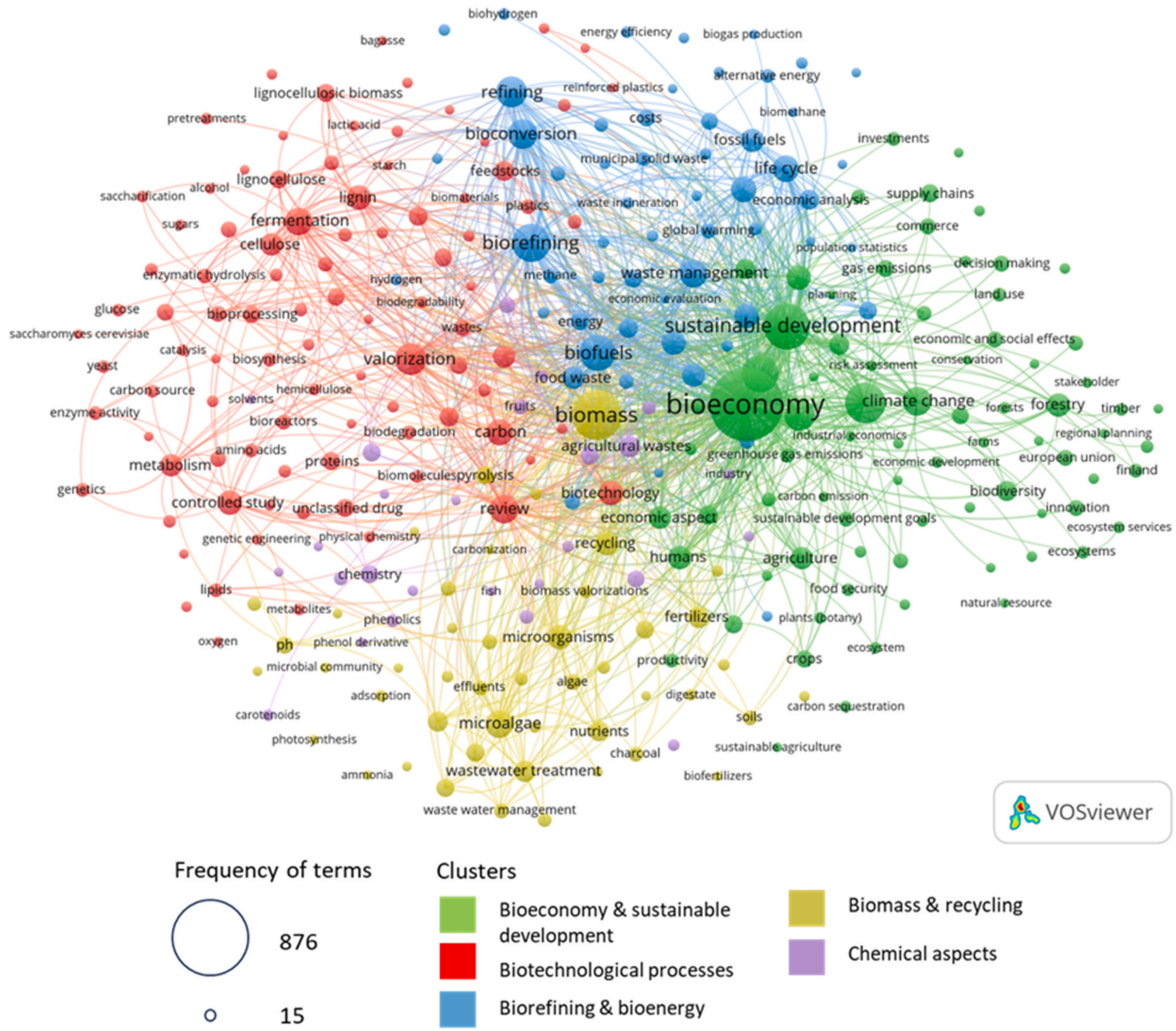

Fig. 1. Keyword network search string 1.

bioeconomy. Distinct differences emerge between the search string's terms, 'model*' (marking 1) and 'simulation' (marking 2).

The node 'modelling' (marking 1) is considerably larger and exhibits connections to various terms, such as 'climate change' or 'bioenergy'. Authors often investigate them together in the context of modelling. Fig. 4 shows that 'modelling' is not directly connected to more specific methods like 'system dynamics' or 'agent-based modelling'. This is because authors frequently use terms such as 'system dynamics' without including 'modelling' in their keywords, and vice versa.

On the contrary, the node representing 'simulation' (marking 2) is one of the smallest in the network - due to the lower bound selected. Furthermore, it shows only one connection to 'bioeconomy', implying a limited exploration of simulation in connection with other prevailing topics such as 'climate change' or 'sustainable development'. For an illustration showing the connection between 'simulation' and 'bioeconomy', see Figure A1. However, it is not in the same cluster as 'bioeconomy', but in the 'biotechnological processes' cluster. This indicates that simulations are primarily used to simulate technical systems, not social systems like value networks with human agents.

However, it is necessary to differentiate between types of simulation. In this context, the primary differentiation lies between technical process simulation and agent-based simulation employed for simulating actor behaviour. Technical process simulation deals with physical phenomena and involves the detailed simulation of physical, chemical or technical processes. In contrast, agent-based simulation is dedicated to modelling and analysing social and individual behaviour. Agent-based simulation aims to understand the emergent dynamics inherent in groups of actors, which need to be considered in the process of establishing new technologies in a sector market.

To examine these simulation aspects more closely, we discuss the nodes 'discrete event modelling', 'system dynamics simulation' (see marking 3, Fig. 3) and 'agent-based modelling' (see marking 4, Fig. 3) in the following section. We use selected literature from the nodes giving examples and showcasing the strengths and weaknesses of the methods.

3.2.1. Simulation methods

The bioeconomy is considered a complex system characterized by interconnected elements and dynamic interactions, ranging from biological resources, agricultural practices, and industrial processes to socio-economic factors like market dynamics, political frameworks, and individual behavioural patterns of actors. Complexity arises as these factors effect socio-technical value networks simultaneously. Changes in one aspect of the bioeconomy can lead to repercussions on other areas, resulting in reactions that are not immediately predictable. Three

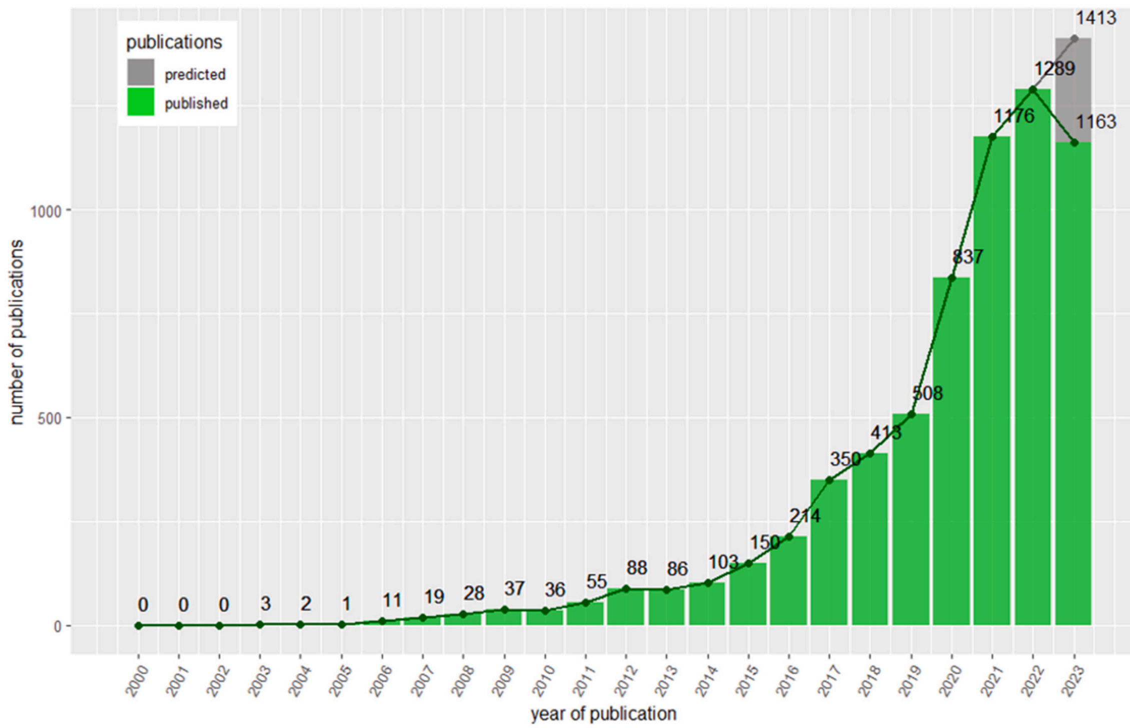

Fig. 2. Number of publications on bioeconomy per year, since 2000 (search string 1; n = 6569); source Scopus, data compiled November 2023.

simulation methods stand out in literature (Dahiya et al., 2018; Hartley et al., 2020; Madear and Madear, 2021) to simulate such complex systems: discrete event simulation, system dynamics, and agent-based modelling. Compared to traditional approaches, these modern simulation methods can overcome limitations of classical numerical methods, such as their equilibrium orientation. Pyka et al. (2022) contend that most existing models are rooted in neoclassical welfare theory, presenting challenges in representing feedback loops and accommodating structural changes. Adopting discrete event simulation, system dynamics, and agent-based modelling can help mitigate these challenges and overcome limitations. These methods can incorporate long-term developments and respond to structural transformations.

Although the network includes nodes for system dynamics modelling and agent-based modelling (see markings in Fig. 1), there is no distinct node for discrete-event simulation. This is because the keyword 'discrete event simulation/modelling' appears only once in the literature of this search string. To ensure informative results, a minimum occurrence threshold of seven is set. Discrete event simulation only appears once, and a network containing only keywords that occur once is not useful, as it would result in considerably more nodes, thus more overlaps and reduced readability.

3.2.2. Discrete event simulation (DES)

The only source within search string number 2 that includes discrete-event simulation as a keyword is the work of Hartley et al. (2020). This research addresses the challenges of operational inefficiency in the supply of corn stover for biofuel production. The authors conducted a stochastic analysis of throughput performance using a discrete event simulation, considering feedstock characteristics in a conventional corn stover supply logistics pre-processing conversion system.

Discrete event simulation is well-suited for modelling discrete events, activities, and interactions in the bioeconomic system, such as harvests or production cycles. It also allows for the inclusion of stochastic elements, facilitating the simulation of uncertainties (Mobini et al., 2014). However, this approach has limitations in depicting continuous changes or trends, crucial in bioecology for understanding long-term ecological trends like biodiversity or soil quality changes. Additionally, while discrete event simulation can account for actors and their decisions, it may not fully capture more complex patterns of interaction between actors and potential collective behaviours (Allen, 2011).

3.2.3. System dynamics (SD)

Using system dynamics (SD) simulation represents another approach in simulation methods, characterized by a predominant use of a top-down approach. This approach may oversimplify complexities and exhibit inflexibility when intricate interactions require consideration of individual components' influence on the overall system.

The connection between the 'system dynamics' node the 'bioeconomy' node in the keyword network (see marking 3, Fig. 3) arises from the joint use of these terms in the keyword listings of some publications (Allena-Ozolina and Bazbauers, 2017; Blumberga et al., 2018; Gravelsins et al., 2017; Hurtado and Berbel, 2023; Morales and Lhuillery, 2021; Roy and Tu, 2022; Runge et al., 2017). The method is characterised by its ability to depict changes over time and feedback loops. For instance, Blumberga et al. (2018) developed a system dynamics model as a general framework for visualising critical sectors in 'biotechonomy', emphasizing innovative technologies for processing bio-resources. Roy and Tu (2022) discuss the importance of biorefinery in bioeconomy strategies and suggest that system dynamics simulation is a suitable method to illustrate the interactions between components of biorefinery supply chains and their response to exogenous factors.

Despite some applications, the system dynamics approach has declined in popularity, particularly since the early 1990s, increasingly supplanted by the agent-based approach (Pyka et al., 2022). The primary reason for this shift lies in the inherent limitation of system dynamics simulation, which, akin to numerous mathematical models, operates at a highly aggregated level (Borshchev and Grigoryev, 2020). Therefore, it is not well-suited for modelling the heterogeneity of actors and the complex interaction patterns in the bioeconomy. Using agent-based simulation to capture these aspects can be advantageous.

3.2.4. Agent-based modelling (ABM)

The third simulation paradigm occurring in the keyword network is

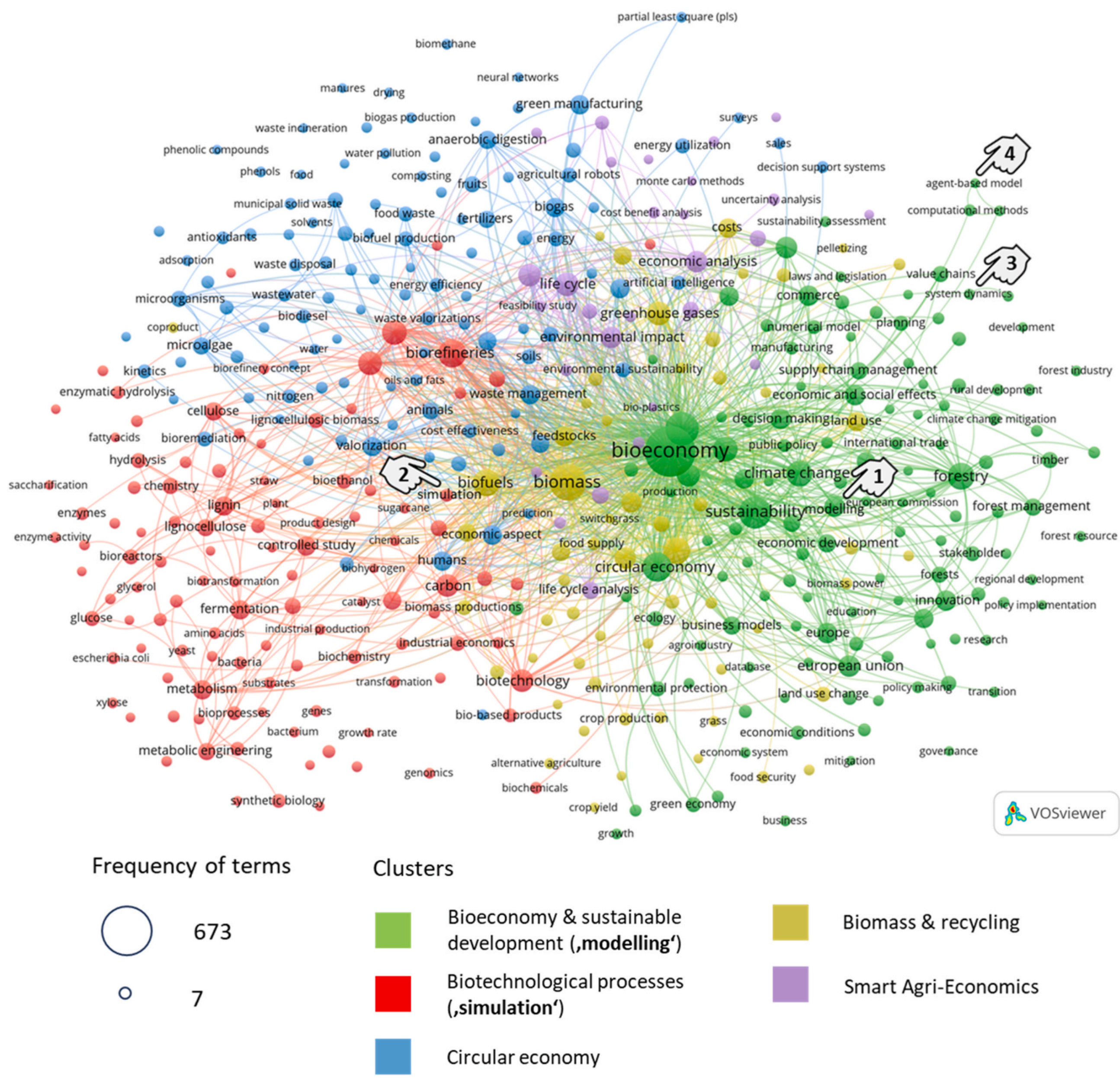

Fig. 3. Keyword network search string 2.

agent-based modelling (see marking 4, Fig. 3). This node lacks a direct connection to the bioeconomy, although it is thematically positioned in the same cluster as SDS. The absence of a visible connection is attributed to the limitation of the visualisation software, which displays only the top 1000 strongest connections. However, a closer look reveals a linkage. In search string 2, papers by Misslin et al. (2022), Leibensperger et al. (2021), Schulze et al. (2017), and Mertens et al. (2016a) all feature both 'agent-based modelling' and 'bioeconomy' in their keyword listings.

Agent-based modelling (ABM) has emerged as a powerful computational approach for simulating dynamic interactions among diverse entities within shared environments, particularly in the context of bioeconomy (Misslin et al., 2022). However, ABM offers potential not only in the bioeconomy but also in other areas, such as transport (Galland et al., 2014) or healthcare (Auchincloss and Diez Roux, 2008), where its use is much more established. This approach is characterised by its emphasis on modelling the behaviours and interactions of individual agents. In doing so, ABM captures a broad range of interactions and feedback, linking agents to their social, economic and ecological surroundings (Pyka et al., 2022). Yang et al. (2022) highlight its computational prowess for simulating the dynamic actions, reactions, and intercommunication among agents in shared environments, allowing for a nuanced understanding of system-level behaviours and dynamics. The flexibility of ABM is particularly advantageous for modelling the decision-making processes of stakeholders in complex systems. Mertens et al. (2018) stress the advantage of ABMs in understanding mechanisms at the micro-level of a system, such as the bioeconomic value chain. ABMs provide a more natural representation of economic systems, offering valuable insights into market mechanisms and decision-making processes within biomass value chains (Mertens et al., 2018).

In contrast to other methods like system dynamics, which employ a top-down approach (Ding et al., 2018; Macal, 2010), agent-based modelling addresses the issue of optimisation differently. While a global optimum may yield the highest overall objective function value, it may not necessarily be the best choice for individuals such as small-scale farmers. If participation in a system is not sufficiently attractive for

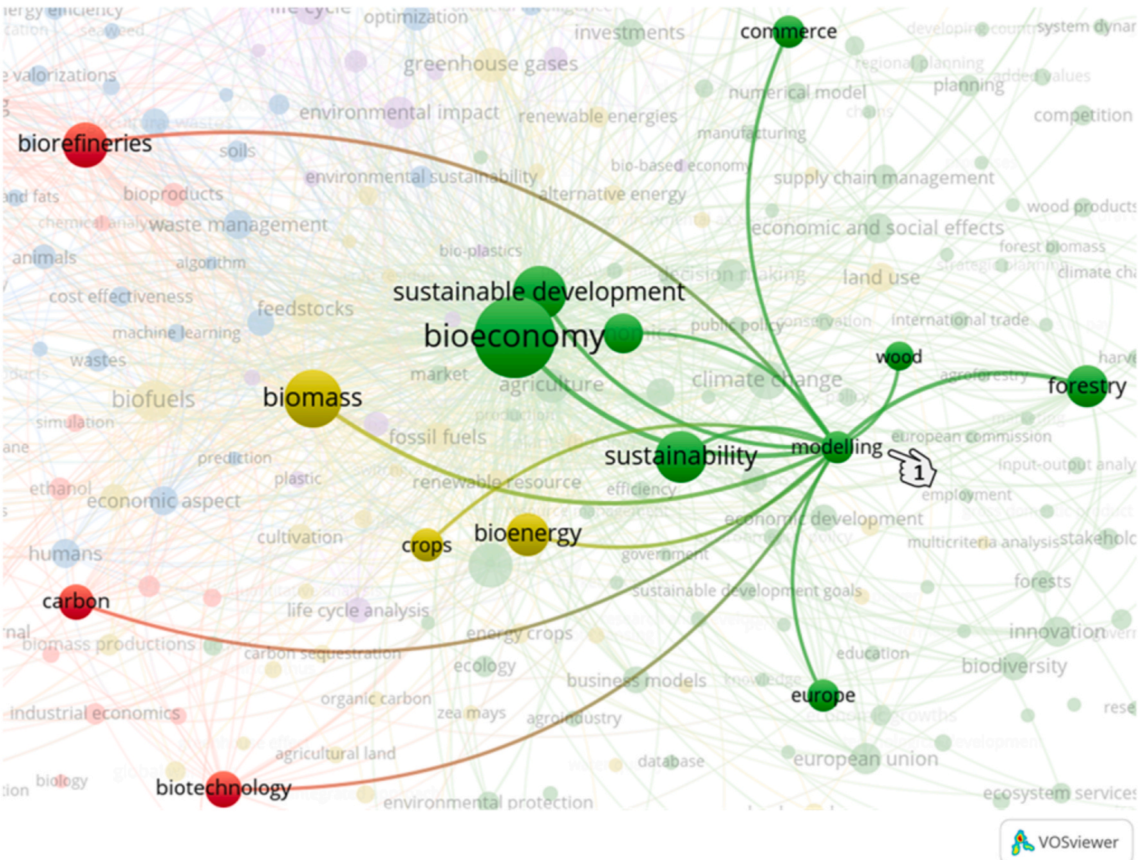

Fig. 4. Focus on 'modelling' (search string 2).

them, they may choose not to participate, leading to their exclusion as potential collaborators in new value chains. ABM is well-suited for depicting the individual behaviour of a heterogeneous model population actors. It employs a bottom-up approach (Pyka et al., 2022; Tesfatsion, 2002), starting from individual agent behaviours and interactions to simulate emergent system-level patterns. This methodology allows for the incorporation of social aspects very effectively. For instance, empirical data on social behaviours and interactions might be directly integrated into an ABM, enabling a more realistic representation of social dynamics within the model. So, we added 'agent-based modelling' as the second extension to the search string.

3.3. 'Bioeconomy', 'Modelling', 'Simulation', 'ABM' - agent-based modelling of the bioeconomy

The final search string contains synonyms of 'bioeconomy', 'modelling', 'simulation', and 'agent-based modelling' (see Table 1). This delimiting search shows 12 publications, which will be reviewed in the following analysis. Although this is a relatively small number, the insights derived are highly instructive. The selected publications provide detailed case studies on specific aspects of the bioeconomy, such as local biomass.

The third network of keywords exhibits a noticeably lower number of nodes or terms (32) than the preceding two (see Fig. 5). This discrepancy is attributed to its foundation on a more limited selection of publications. The primary terms within this network comprise 'agent-based modelling', 'autonomous agents', and 'computational methods'. Nevertheless, the terms 'bioeconomy' and 'modelling' are also represented. For a detailed breakdown of the keywords of the respective publications, see Table A2.

It is noteworthy that the term 'simulation' has no corresponding node. This is because the 12 publications forming the basis of the network do not contain 'simulation' in the keywords. However, 'simulation platform' is listed as an indexed keyword in the papers by Yang et al. (2022) and Viridi et al. (2019) and thus appears in the network.

The publications in search string 3 were published between 2016 and 2022. The first articles were published in 2016, emphasizing that agent-based modelling is a new research focus within the context of the bioeconomy. This first publication analyses the influence of the market environment on the purchase of local biomass for anaerobic digestion using an ABM. In 2023, no publications on this subject have been recorded. However, an observable upward trend shows a growing interest in this field. To check the content of the literature on this subject, it is imperative to confirm the availability of full-text articles. This requirement is not met for one of the papers by Mertens et al. (2016b). Consequently, this one is not part of the further analysis. An overview of the publications analysed below can be found in Table A3.

In search string 3, the authors of 10 of the 12 remaining publications develop and apply an ABM at micro-level. These studies explore explicit examples or specific regions, offering insights that can potentially be scaled up to the broader context of the bioeconomy. Frequently, these efforts entail analysing recycling processes or exploring the complexities of the circular economy. Mertens et al. (2016a) delve into the challenge biogas plant managers face, focusing on securing biomass at stable prices. Their ABM investigates how market dynamics influence the procurement of local biomass for anaerobic digestion, with a specific focus on the silo market in Flanders (BEL). They use dairy farmers and one biogas plant as agents. While their ABM provides valuable insights, certain limiting assumptions should be mentioned. The model assumes static farmers' behaviour over time. The use of triangular distributions for parameters lacking empirical data introduces uncertainties. Moreover, excluding certain market mechanisms highlights the need for a

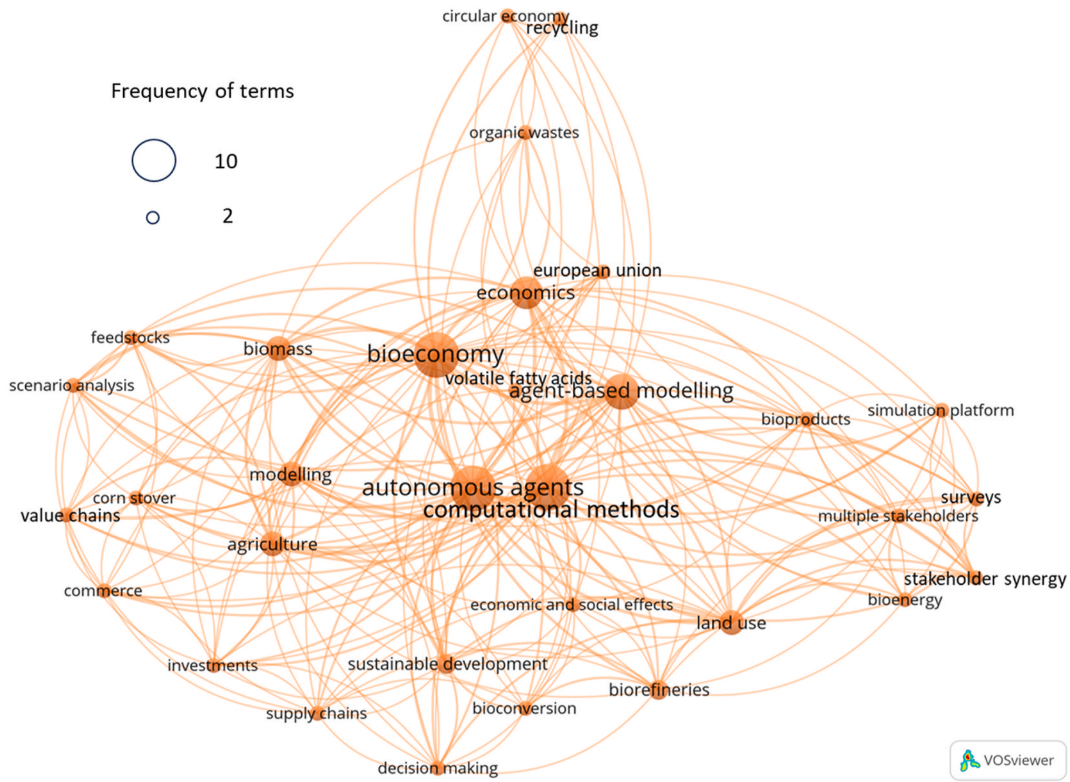

Fig. 5. Keyword network search string 3.

more comprehensive representation. The study's insights underscore the importance of the local context for biogas plant operators, offering valuable contributions to assessing the consequences of biomass utilisation in various local processes.

Similarly, Schulze et al. (2017) leverage ABM to gain theoretical insights into the economic and environmental determinants influencing the expansion of short-rotation forestry (SRF). The model developed captures the decision-making processes of profit-maximising farmers, offering a comprehensive mechanistic understanding of SRF expansion. The study considers general economic determinants and site-dependent factors, shedding light on their impact on SRF expansion. Investment theory aspects like long-term investment decisions and individual risk attitude improve the model. On the critical side, certain assumptions in the model may limit its predictive accuracy. For instance, assuming a stable willingness to pay for SRF products and neglecting changes in farmers' behaviour over time might oversimplify the dynamic nature of agricultural systems.

Continuing the exploration of challenges in securing a continuous raw material supply, Mertens et al. (2018) developed an ABM 'to help [them] understand the factors at the micro-level (e.g. actors' willingness to participate, reliability of supply, and actors' coordination) that lead to the challenge observed at the macro-level, ensuring a continuous feedstock supply' (Mertens et al., 2018, p. 211). A central limitation of the study lies in its static approach to assessing willingness, providing only a snapshot. The authors propose the utilisation of panel surveys to account for evolving economic conditions. (Mertens et al., 2018) use an ABM to investigate the factors influencing the continuous supply of agricultural residues, specifically corn stover, for biorefineries. The study demonstrates that improved coordination among stakeholders can significantly enhance supply reliability. For instance, better coordination scenarios, such as bioprocessing cooperatives, improved farmers' willingness to participate by up to 51% (Mertens et al., 2018).

Viridi et al. (2019) adopt agent-based modelling to simulate a bioeconomy system, comparing three different farming systems (conventional farming, organic farming, and smart farming). In contrast to the previous models, weather (temperature and precipitation), soil, and plants serve as agents rather than humans. This study emphasizes the promising results of smart farming yet points out the need for increased investment. However, it is crucial to recognise that such an isolated examination of farming systems may not provide a comprehensive understanding of the bioeconomic landscape. Incorporating a systemic view is imperative to avoid solely scrutinising a fragment of the value chain. By adopting a holistic perspective, researchers can better comprehend the interconnectedness and interdependencies within the bioeconomy, facilitating more informed decision-making processes and policy formulation.

The work by Fernandez-Mena et al. (2020) applies the FAN (Flows in Agro-food Networks) model to simulate material flow scenarios in a small economic region in France. They advocate using ABMs, such as FAN, as a foundation for designing policies and regulations, especially those seeking fundamental changes in circular agricultural and food systems. In their work, Fernandez-Mena et al. (2020) primarily focus on the biotechnological and logistical aspects of material flows. Social factors related to interactions among agents, such as the fact that farmers do not always act rationally and optimally, are disregarded. They simulate material exchange based on a stochastic algorithm that considers factors like the distance between agents or preference coefficients for specific uses of materials. The additional incorporation of human characteristics would pose a challenge due to data collection and modelling complexity. However, it could provide significant added value for a realistic simulation in conjunction with the existing model. Despite these limitations, ABMs like the FAN model can support a more holistic process to design agricultural and environmental policies and regulations. For example, this study demonstrates significant potential process improvements, such as a reduction of GHG emissions of up to 12.8 Gg of CO_2-equivalent per year. Also, the circularity of nitrogen flows and enhanced local food production sustainability were improved. Additionally, biogas production reached over 9 million cubic meters, translating to 18.4 GWh of electricity, enough to power 3942 households annually, demonstrating significant energy and resource efficiency improvements (Fernandez-Mena et al., 2020).

Leibensperger et al. (2021) focus on synergies among various stakeholders in developing cellulosic biofuels. An ABM is employed to simulate interactions among stakeholders (producers, consumers, biorefineries, rural communities, and the government). Specifically, they investigate how the reactions of different stakeholders' interplay and how these reactions influence each other's decisions and the overall system performance. The study highlights several key improvements and potential benefits of optimized stakeholder coordination. For instance, the study emphasizes the importance of continuous investment in research and pilot projects to overcome technological and logistical barriers in cellulosic biofuel production. They estimate that the cost of cellulosic biofuel production is around 0.7–1.1 $/l, compared to 0.4–0.7 $/l for corn ethanol, suggesting that technological advancements and subsidies are crucial for making cellulosic biofuels economically viable (Leibensperger et al., 2021). The authors opt for an ABM, noting that 'ABM derives system-level outcomes through simulation of heterogeneous individual agents and their interactions' (Leibensperger et al., 2021, p. 9). Moreover, they argue that the suitability of ABM for modelling complex systems is underscored by the inherent heterogeneity among agents and the presence of feedback loops between them. ABM excels in capturing scenarios where the outcomes of interactions among individuals transcend mere aggregation.

Velghe et al. (2021) explore the Volatile Fatty Acid Platform (VFAP) as a cornerstone for the circular bioeconomy. Their ABM, SIM-VOLATILE, models the waste treatment industry as a complex system. The agents in the model represent actors within the waste treatment industry that make decisions regarding adopting VFAP technologies based on economic feasibility, social pressure and market size. The inclusion of social pressure reflects the dynamic interactions between agents, capturing the influence of societal awareness towards green technologies. While economic incentives such as gate fees are incorporated, the absence of a comprehensive system view limits understanding the interplay between various factors influencing VFAP adoption. Therefore, while the model provides valuable insights into economic and social dynamics, future iterations should integrate a systemic approach to account for the multifaceted nature of bioeconomic systems. The study reports that VFA yields from various types of biowaste were significant, with food waste achieving an average yield of 627 g COD/kg organic matter (OM), vegetable, garden, and fruit waste (VGF) yielding 448 g COD/kg OM, and the organic fraction of municipal solid waste (OF-MSW) yielding 384 g COD/kg OM (Velghe et al., 2021). COD, or Chemical Oxygen Demand, measures the amount of oxygen required to oxidize the organic matter in the sample, serving as an indicator of organic pollutant levels. These results underscore the potential for significant material recovery from biowaste, contributing to cleaner and more sustainable production processes. Additionally, the use of membrane filtration technology for VFA concentration demonstrates low energy consumption and operational scalability, further enhancing the sustainability of the process (Velghe et al., 2021).

Yang et al. (2022) further extend the model introduced by Leibensperger et al. (2021). The study focuses on developing an agent-based modelling tool to facilitate communication among the bioenergy and bio-product stakeholders, particularly in advancing the cellulosic bioeconomy. The focus is on integrating agents representing the relevant actors and decision-makers in the cellulosic bioeconomy, aiming to simulate their interactions and decisions within a dynamic environment. In Leibensperger et al. (2021) and Yang et al. (2022), the model consists of five types of agents and encompasses five aspects of conditions/factors affecting agents' behaviours, interactions, and overall system performance. These include economic, environmental, social, technical, and policy factors. The ABM in Yang et al. (2022) offers valuable insights into general trends and patterns within the simulated cellulosic bioeconomy system. For example, in a pilot study in a Central Illinois watershed, the model demonstrated that a long-term policy commitment and subsidies for small-scale bio-facilities could enhance biofuel production and reduce nitrogen emissions in the watershed. For example, providing a 100 $/acre subsidy for Total Maximum Daily Load (TDML) reduced nitrogen loading in the watershed below the prescribed cap within 10 years, indicating substantial environmental benefits from targeted policy interventions (Yang et al., 2022). However, the model is subject to uncertainties, particularly regarding dynamics in the system, such as uncertainties in crop yields, prices, and consumer willingness to pay. In further research, exploring the potential synergies of integrating this model with other complementary models may be beneficial, thereby enriching the analysis and fostering a more comprehensive understanding of the bioeconomic landscape. For instance, it could be advantageous to integrate ABM with a macro-economic model to capture the impacts on the overall economic sector or to integrate environmental models to assess the environmental impacts of bioeconomic activities and promote sustainable practice. There are already examples of combining ABM with a macro-economic model, such as the work by Niamir et al. (2020). In this study, ABM is integrated with a computable general equilibrium model (CGE) to scale behavioural changes among heterogeneous individuals regarding energy decisions while tracking their macro-economic and cross-sectorial impacts. Besides the combination with a macro-economic model, we see the potential for a combination of Yang et al. (2022) work with a model simulating biorefinery technology diffusion. Combining could provide a more thorough understanding of the factors influencing biorefinery adoption and proliferation, leading to better policies for sustainable bioeconomic growth. In the most recent work, Misslin et al. (2022) develop the MAELIA-OMW (agro-environmental and socio-economic modelling and assessment tool for territorial management of organic resources), an integrated assessment and modelling approach that combines a soil-crop model with a farmer ABM and multicriteria analysis. The study, applied to the Versailles Plain, France, compares scenarios of organic and mineral fertilization. The objective is to understand the trade-offs and synergies between biomass management strategies. Key findings include that the potential scenario increased soil organic carbon (SOC) storage by 11% compared to the mineral-only scenario. However, this also led to a 56.2% increase in greenhouse gas (GHG) emissions due to higher nitrogen losses. Additionally, organic fertilization scenarios resulted in a 96.1% increase in fertilization workload, emphasizing the trade-offs between improved soil quality and increased environmental impact (Misslin et al., 2022). One aspect of this work that could draw scrutiny is its modelling of farmers' strategies. These rely on IF-THEN decision rules. While using IF-THEN decision rules is a standard method, the real world is more complex, and various factors, including social ones, influence farmers' decisions, but they are challenging to model appropriately. Social aspects, such as long-term business interactions between organic waste producers (a compost platform, a livestock farm, and horse farms) and users (farmers), could introduce additional dimensions into the model. The two remaining sources diverge somewhat in their thematic focus. In contrast to the other works, these sources do not concentrate on a specific aspect or process within the bioeconomy. Instead, they engage in a comparative analysis of different models and modelling approaches.

Vance et al. (2022) contribute to sustainable assessments in novel biorefinery systems by discussing challenges and methods related to life cycle analysis (LCA). Agent-based modelling is briefly mentioned as an alternative to system dynamics: '[…] agent-based modelling is more applicable to consequential LCA, a fact highlighted by several studies' (Vance et al., 2022, p. 10).

A distinctive position in literature is currently held by the work of Pyka et al. (2022). Unlike the development and application of an ABM, this study involves comparing different models for bioeconomy modelling. The authors highlight ABM as a method, showcasing its potential and viewing it as an opportunity to enhance and complete bioeconomic models. They particularly see potential in combining socio-economic and environmental ABMs in the evolving landscape, stating, 'Most interesting for bioeconomy modelling are recent attempts to combine socio-economic and environmental ABMs (Pyka et al., 2022, p. 7). Pyka et al. (2022) highlight different areas where traditional models fall short and emphasise the advantages of the new approach. They identify a need to enhance agent behaviour rules, often relying on oversimplified assumptions or un-validated utility functions. The authors emphasise the necessity to incorporate a more comprehensive representation of environmental processes affected by bioenergy development and propose the simulation of complex interactions among multiple stakeholders, including those not directly involved in the bioenergy supply chain.

The consideration of material use of biomass is crucial. Integrating the material use aspect ensures that the simulation captures the full spectrum of potential outcomes and synergies emerging from the bioenergy and bio-based material coexistence, thereby providing a more accurate representation of the broader implications of bioeconomic strategies. Pyka et al. (2022) conducted a classical literature review with a systematic literature search. Yet, a combination with bibliometric analysis can help structure the literature and identify best practices in modelling the bioeconomy and interdisciplinary research gaps.

Despite the findings obtained by analysing the literature from search string 3, not all publications in this area contain concrete quantitative figures, which makes it difficult to draw standardised comparisons. This lack of standardisation hinders the optimal selection of modelling approaches. To address this issue, comparative studies are needed that systematically evaluate different (simulation) modelling applications within the bioeconomy. Such studies would provide a more nuanced understanding of the strengths and weaknesses of different approaches, thereby facilitating more informed decision-making.

In conclusion, exploring literature on agent-based modelling in the context of bioeconomy reveals a diverse landscape of studies and a research gap for investigating underrepresented, promising modelling approaches. Each key finding is linked to the main goals of the study.

(1) Comprehensive Review - The identified publications offer a detailed overview of the current state of ABM in bioeconomy research.
(2) Identify Research Gaps - Significant gaps were found in the areas of biorefinery technology modelling and stakeholder behaviour analysis.
(3) Support Sustainable Practices - The results demonstrate how ABM can enhance bioeconomic modelling and help reduce environmental impacts in bioeconomic activities.

4. Discussion

The bibliometric analysis identified 6569 publications (after search string 1) on the bioeconomy. Narrowing down to studies on bioeconomy modelling and simulation resulted in 1324 publications, and further focusing on agent-based modelling (ABM) yielded 12 key publications. These steps highlighted essential contributions in bioeconomy modelling, particularly the role of ABM in understanding complex bioeconomic systems. Out of the 11 publications with full-text availability, 10 focus on micro-level use cases, wherein agent-based models were developed and applied across various bioeconomy scenarios. The remaining two publications adopted a comparative approach at the macro-level, presenting different models and modelling methods for the bioeconomy. The ability of ABMs to capture individual decision patterns and simulate the dynamic interactions between heterogeneous agents allows for a thorough understanding of complex bioeconomic systems. Furthermore, ABM allows for modelling various timescales, capturing both short-term dynamics and long-term trends (Fernandez-Mena et al., 2020; Schulze et al., 2017). Being able to use feedback loops in agent-based simulation is crucial for realistically modelling dynamic interactions over an extended period, adapting to system changes, and facilitating policy changes (Velghe et al., 2021). This examination of the literature has revealed that different authors, such as Pyka et al. (2022) and Yang et al. (2022), emphasise the necessity to incorporate a more comprehensive representation of environmental processes affected by bioeconomy development. This implies that existing models lack a sufficient connection between stakeholder decisions and their environmental consequences, revealing a limitation in addressing the broader impact of bioeconomic systems. The authors propose the simulation of complex interactions among multiple stakeholders, extending beyond the traditional focus on the bioenergy supply chain. This recognition of the need for a more holistic representation of stakeholders shows that conventional models might overlook significant contributors and influences in the bioeconomic landscape. ABM is a promising approach to overcome these limitations, providing a valuable tool for researchers to explore and understand the intricate dynamics of the bioeconomy. However, a crucial aspect for advancing and implementing the bioeconomy that is barely addressed in the analysed publications is the specific requirements of new technologies like biorefineries. Developing biorefinery concepts in the context of the bioeconomy could provide significant added value for the economy, society, and the environment. Economically, efficient biorefinery concepts could lay the foundation for sustainable and cost-effective production processes, potentially leading to economic growth and competitiveness. Societally, such concepts could promote job creation, especially in rural areas, and support the transition to a more sustainable economy. From an environmental perspective, biorefinery concepts could encourage using renewable resources and reduce dependence on non-renewable raw materials.

Despite these advantages, only 4 of the 11 publications address this aspect (Leibensperger et al., 2021; Vance et al., 2022; Velghe et al., 2021; Yang et al., 2022). Velghe et al. (2021) mention biorefineries briefly, focusing instead on the novel volatile fatty acid platform. Vance et al. (2022), on the other hand, extensively explore the sustainability assessment of biorefineries, advocating for a combined approach using life cycle assessment (LCA) with system modelling tools (ABM and SD). However, their primary emphasis is on LCA, neglecting the dynamic process of technological diffusion of integrated biorefineries. Only two works extensively explore this aspect of technological diffusion of biorefineries: Leibensperger et al. (2021) and Yang et al. (2022). Leibensperger et al. (2021) model biorefineries as an agent type in their model. However, they acknowledge a limited understanding of, for example, farmers' behaviour in this context. To address this gap, future studies should conduct additional surveys among biofuel producers and gather further data on agent behaviour and decision-making.

Yang et al. (2022) have advanced the model of Leibensperger et al. (2021), highlighting aspects such as the ability of community agents to influence the establishment of new biorefineries. Nevertheless, this model is still fraught with uncertainties, necessitating investigation with stochastic versions of ABM. Additionally, the model relies on simplifications, such as simplifying the technology development process. In practice, national policies, R&D investments, and market development activities could significantly influence and accelerate this process. Future studies should further incorporate the interactions between technology, policy, and the market to comprehensively assess the impacts on the emergence of the bioeconomy.

The outcome of these 11 publications was significantly influenced by the combined methodology of bibliometric analysis and a systematic approach. This approach provides a thorough overview of research investigations, methods used, and existing connections within the research field. Visualising search string 2, it became evident that the presence of agent-based modelling in the bioeconomy domain is currently limited. Through a systematic refinement of the search string, this connection was visualised clearly (see Fig. 5). Thus, the study provides an overview of the current literature on simulation modelling in the bioeconomy, highlighting key trends and identifying research gaps. This analysis is crucial for understanding the current state of research and pinpointing areas that require further exploration. The study contributes to the discussion about how effective agent-based modelling is in capturing the complexity of bioeconomic systems. By simulating the behaviours and interactions of diverse stakeholders, such as farmers, consumers, and policymakers, ABMs provide detailed insights into how individual actions contribute to system-wide outcomes. This is particularly important for understanding how policy interventions can influence bioeconomic activities. The study addresses the potential of ABM to integrate social, economic, and environmental dimensions. This integration is vital for developing sustainable bioeconomic strategies that balance ecological health, economic viability, and social well-being.

The detailed analysis of publications shows that the impact of these models on cleaner and more sustainable production can be profound. ABMs enable the cost and emission-saving simulation of sustainable practices, such as the adoption of biorefineries and renewable energy technologies, demonstrating their potential to reduce greenhouse gas emissions and promote resource efficiency. For example, studies have shown that stable biomass supply chains and efficient waste recycling can significantly enhance the sustainability of bioeconomic activities (Fernandez-Mena et al., 2020; Mertens et al., 2018). These insights are crucial for achieving long-term sustainability goals.

Despite the valuable insights the reviewed approaches provide, each method has its limitations. While effective in capturing individual decision patterns and dynamic interactions, agent-based models often require substantial computational resources and detailed empirical data, which can limit their applicability and scalability. On the other hand, system dynamics models may oversimplify complex interactions by operating at a high level of aggregation, potentially overlooking heterogeneous agent behaviours. While suitable for process optimisation, discrete event simulations may not fully capture long-term ecological trends or collective behaviours. These limitations suggest that the conclusions drawn from these models should be interpreted with caution, acknowledging the potential for oversights and the need for further refinement in future research.

Also, the review is not without limitations. There is the exclusion of grey literature, considering only high-quality peer-reviewed papers (Scopus database). Secondly, some studies related to (agent-based) modelling of the bioeconomy are missing in our research because they do not explicitly use the terms 'bioeconomy' and 'agent-based modelling' in their title, abstract, or keywords. In some instances, only partial aspects of the bioeconomy are used as keywords, such as 'agricultural policy analysis' (Happe et al., 2006) or 'farmers behavior' (Burg et al., 2021). In some cases, authors have not defined any keywords, and the keywords added by the database do not suit the search string (Brown et al., 2019). Examples of such excluded studies, despite their thematic relevance, are the works by Burg et al. (2021), Happe et al. (2006) and Brown et al. (2019). It is crucial to note that 'bioeconomy' is a collective term that requires subdivision to capture relevant sources that use more established wording. Keywords such as 'agricultural biogas facilities', 'future prospect', or 'land use change' are integral terms within the bioeconomy. Another limitation is the exclusive use of Scopus. While among the largest global databases, Scopus (Elsevier) does not give access to all bioeconomy publications. Other international databases, such as Crossref (Crossref) or Web of Science (Clarivate Analytics), could offer additional literature network connections.

Despite these limitations, our analysis reviews how agent-based modelling is currently established in bioeconomy literature. The limited number of 12 publications, including the 11 analysed and the one inaccessible due to unavailability of its full text, identified in search string 3 demonstrates the great potential for further research in the field of agent-based modelling in the context of bioeconomy. This selection represents a specific subset of the research landscape, allowing for the identification of research gaps within this particular domain. The analysis showcases how nuanced exploration of this research segment can contribute significantly by highlighting less-explored aspects and suggesting potential research directions. There is room for research to extend the existing models, design new ones, incorporate different types of agents, or investigate the effects of changing policies on the market diffusion of new technologies. The additional value of our review approach lies in combining a conventional literature review and a visualised bibliometric analysis, providing a valuable tool for comprehensively understanding the multidimensional nature of bioeconomy through the analysis of extensive literature databases.

5. Conclusions

This study presents a comprehensive literature analysis of the use of agent-based modelling (ABM) within the bioeconomy, addressing key research questions and highlighting significant trends, gaps, and policy implications. Our analysis reveals that ABM is effectively applied across various domains in the bioeconomy, such as biorefineries, biomass supply chains, and bioenergy production. These applications demonstrate ABM's ability to optimize resource use, simulate stakeholder interactions, and assess the impacts of technological innovations. Despite the versatility and effectiveness of ABM, our study identified several limitations in the current research. Most studies do not comprehensively integrate socio-economic factors or long-term environmental impacts, focusing instead on immediate technological and economic outcomes. ABM's bottom-up approach, starting at the individual level and aggregating to understand system-wide phenomena, provides a detailed insight into interactions, considering diversity and heterogeneity. In contrast, the top-down approach, often used in system dynamics and general equilibrium models, may oversimplify reality by focusing on overarching structures and trends, potentially overlooking individual differences. A resilient bioeconomy is characterised by complex, decentralised decision structures. Neglecting these structures in modelling might lead to ineffective recommendations for action and hinder the development of a sustainable bioeconomic production. These limitations suggest that while ABM provides valuable insights, there is a need for more holistic models that incorporate a broader range of factors and scenarios. Future research should aim to integrate socio-economic dimensions and long-term environmental impacts more thoroughly, as well as explore a wider variety of policy interventions to fully understand their potential effects on bioeconomic systems.

The findings of this study underscore the potential of simulation modelling approaches, especially ABM, to address the complexity and dynamic of bioeconomic systems and inform sustainable policy-making. However, addressing the identified research gaps is crucial for advancing the field. Enhancing simulation modelling capabilities to model diverse scenarios and integrating more comprehensive data can lead to more robust and actionable insights. Future studies could undertake additional surveys among stakeholders (e.g. farmers and policymakers) to collect valuable data and insights into agents' behaviour and decision-making processes. Taking into account the perspectives and needs of potential value chain partners can support the implementation of successfully demonstrated technologies and the mobilization of biomass potentials to enable the transition to a more sustainable bioeconomy.

CRediT authorship contribution statement

Raphael Heck: Writing – review & editing, Writing – original draft, Visualization, Software, Formal analysis, Conceptualization. **Leonie Frei:** Writing – review & editing, Writing – original draft, Visualization, Software, Formal analysis. **Andreas Rudi:** Writing – review & editing. **Frank Schultmann:** Writing – review & editing, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly and ChatGPT in order to mitigate grammatical errors and improve language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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

Table A1
Search parameters employed to generate keyword networks Figs. 1, 3 and 5

Figure	Parameters Used in the Analysis
Fig. 1	Data generated by Scopus, accessed November 8, 2023. Search for bioeconomy in Title, Abstract and Keywords (TITLE-ABS-KEY ('bioeconomy' OR 'bio-economy' OR 'bio economy'). VOSviewer display of co-occurences limited to keyword threshold 15.
Fig. 3	Data generated by Scopus, accessed November 8, 2023. Search for bioeconomy and modelling or simulation in Title, Abstract and Keywords (TITLE-ABS-KEY (('bioeconomy' OR 'bio-economy' OR 'bio economy' AND ('model*' OR 'simulation')). VOSviewer display of co-occurences limited to keyword threshold 7.
Fig. 5	Data generated by Scopus, accessed November 8, 2023. Search for bioeconomy and modelling or simulation and agent-based modelling or simulation in Title, Abstract and Keywords (TITLE-ABS-KEY (('bioeconomy' OR 'bio-economy' OR 'bio economy' AND ('model*' OR 'simulation') AND ('agent-based model*' OR 'agent based model*' OR 'ABM'). VOSviewer display of co-occurences limited to keyword threshold 2.

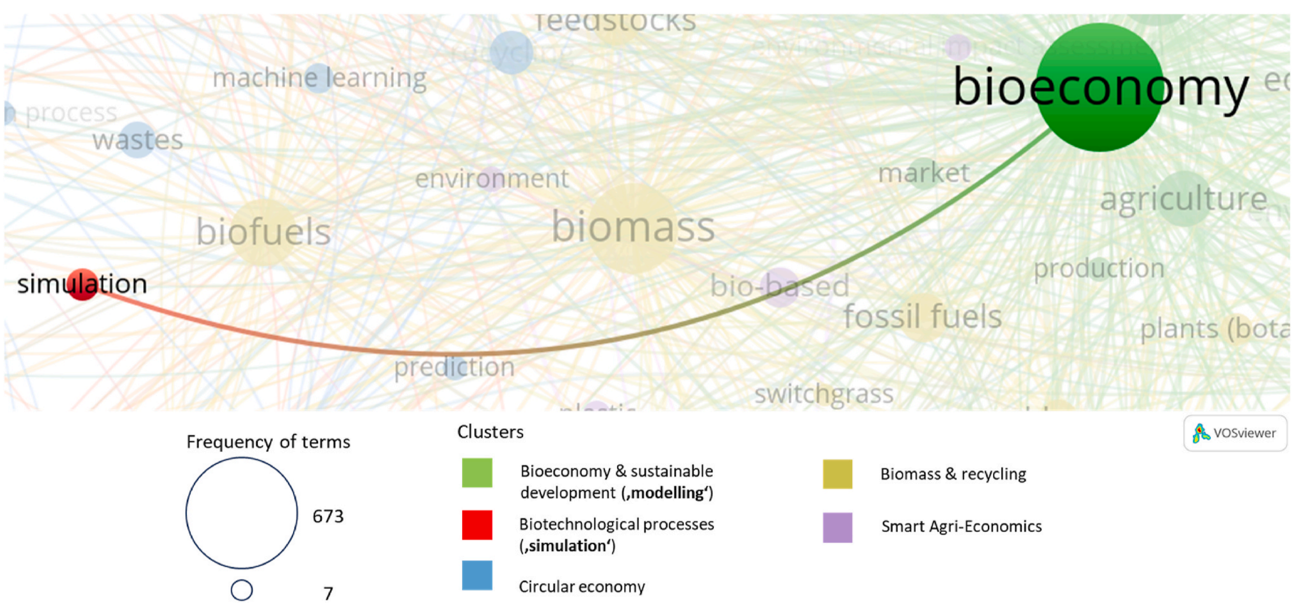

Fig. A1. Focus on 'simulation' (search string 2).

Table A2
author keyword matrix

	Misslin et al. (2022)	Yang et al. (2022)	Vance et al. (2022)	Pyka et al. (2022)	Velghe et al. (2021)	Leibensperger et al. (2021)	Fernandez-(2020)	Viridi et al. (2019)	Mertens et al. (2018)	Schulze et al. (2017)	Mertens et al. (2016a)
agent-based modeling	x	x			x	x		x	x	x	x
agriculture									x	x	x
autonomous agents	x	x	x	x		x		x	x	x	x
bioconversion			x								
bioeconomy	x		x	x		x	x			x	x
bioenergy		x				x					
biomass					x				x	x	x

(continued on next page)

Table A2 (*continued*)

	Misslin et al. (2022)	Yang et al. (2022)	Vance et al. (2022)	Pyka et al. (2022)	Velghe et al. (2021)	Leibensperger et al. (2021)	Fernandez-(2020)	Viridi et al. (2019)	Mertens et al. (2018)	Schulze et al. (2017)	Mertens et al. (2016a)
bioproducts		x		x							
biorefineries			x			x					
circular bioeconomy			x		x						
circular economy	x						x				
commerce											x
computational methods	x	x	x	x		x		x	x	x	x
corn stover									x		
decision making			x							x	
economic and social effects			x	x							
economics	x	x		x	x				x	x	
european union				x	x						
feedstocks									x		x
investments										x	
land use		x	x			x				x	
modeling				x	x				x		
multiple stakeholders		x				x					
organic waste	x				x						
recycling	x						x				
refining			x								
scenario analysis									x		x
simulation platform		x						x			
stakeholder synergy		x				x					
supply chains			x								
surveys		x				x					
sustainable development			x							x	
value chains									x		
volatile fatty acids					x						

Table A3
publications in search string 3

Author	Year	Title	Country	Journal	total Citations
Application cases					
Mertens et al.	2016a	Context Matters – Using an Agent-Based Model to Investigate the Influence of Market Context on the Supply of Local Biomass for Anaerobic Digestion	Belgium	Bioenergy Research	6
Schulze et al.	2017	The expansion of short rotation forestry: characterisation of determinants with an agent-based land use model	Germany	GCB Bioenergy	13
Mertens et al.	2018	Ensuring continuous feedstock supply in agricultural residue value chains: A complex interplay of five influencing factors	Belgium	Biomass and Bioenergy	21
Viridi et al.	2019	Simulation of bioeconomy system using agent-based model in the case of smart, green, and conventional farming	Indonesia	IOP Conference Series: Earth and Environmental Science	6
Fernandez-Mena et al.	2020	Co-benefits and Trade-Offs From Agro-Food System Redesign for Circularity: A Case Study With the FAN Agent-Based Model	France, Canada	Frontiers In Sustainable Food Systems	19
Leibensperger et al.	2021	The synergy between stakeholders for cellulosic biofuel development: Perspectives, opportunities, and barriers	United States	Renewable and Sustainable Energy	29
Velghe et al.	2021	Volatile fatty acid platform - a cornerstone for the circular bioeconomy	Belgium, Germany	FEMS Microbiology Letters	7
Yang et al.	2022	An agent-based modelling tool supporting bioenergy and bio-product community communication regarding cellulosic bioeconomy development	United States, China	Renewable and Sustainable Energy Reviews	4
Misslin et al.	2022	Integrated assessment and modelling of regional recycling of organic waste	France	Journal of Cleaner Production	5
comparative literature					
Pyka et al.	2022	Modelling the bioeconomy: Emerging approaches to address policy needs	Belgium, Germany, Finland, Netherlands	Journal of Cleaner Production	21
Vance et al.	2022	Space, time, and sustainability: The status and future of life cycle assessment frameworks for novel biorefinery systems	Ireland	Renewable and Sustainable Energy Reviews	23

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