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Bioeconomy futures: Expectation patterns of scientists and practitioners on the sustainability of bio-based transformation

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Abstract

Economic sectors relying on the use of biological organisms, processes, and principles to create products and services are expected to experience accelerated growth due to innovation in the bioeconomy. Associated benefits and risks for sustainable development are increasingly subject to societal debate. We compiled expectation patterns from a global survey with bioeconomy experts and a systematic literature review identifying areas of consensus and controversy across dimensions of the sustainable development goals (SDG). Positive connotations dominated in both expert opinions and the scientific literature, but the level of consensus varied across sectors of the bioeconomy and in relation to applied methodological approaches (scientific literature) and type of employer (experts). In both sources, we found more differentiated views on potential impacts of bioeconomic development pathways on sustainability in more established bioeconomy-related discourses, which indicates that expectation patterns in more recent fields of bio-based innovation are subject to early “hype cycle” dynamics. Our findings suggest the need to systematically mainstream sustainability risk appraisals across relevant application contexts in technology impact assessments for the bioeconomy.

KEYWORDS

biotechnology, circular economy, energy, environmental policy, green growth, innovation, pharmaceuticals, sustainable development

1 | INTRODUCTION

The impacts of climate change, unprecedented rates of biodiversity loss, population growth and an ever-growing need for food, energy, and materials, are daunting global challenges of the Anthropocene. In a search for solutions and fueled by rapid technological progress in key enabling technology areas, such as digital and biotechnologies, policy makers increasingly adopt visions of bioeconomic transformation toward greater sustainability (Dietz, Börner, Förster, & von Braun, 2018).

Bioeconomy has been defined in a number of ways with varying emphasis on selected economic sectors. The German Bioeconomy Council, for example, defines bioeconomy as “the knowledge-based production and use of biological resources to provide products, processes, and services in all economic sectors within the frame of a sustainable economic system” (von Braun, 2014; The German Bioeconomy Council, 2013). Similarly, the FAO understands bioeconomy “as the knowledge-based production and utilization of biological resources, biological processes, and principles to sustainably provide goods and services across all economic sectors” (Dubois & San Juan, 2016). By these

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definitions, unsustainable bioeconomic innovations and processes are excluded. In reality, however, most innovations promoted under the label of bioeconomy lack a systematic evaluation of their sustainability effects and trade-offs. Therefore, we adopt a sector-based definition of bioeconomy that does not *a priori* exclude non-sustainable manifestations of bioeconomy including bio-based economic sectors (e.g., agriculture; forestry; bio-based pharmaceuticals, cosmeceuticals, and natural products; organic waste treatment; and bioenergy, bioplastics, and biochemicals, compare Biber-Freudenberger, Basukala, Bruckner, & Börner, 2018).

There is an ongoing scholarly and political discourse about the benefits and risks of the bioeconomy (Biber-Freudenberger et al., 2018; Dietz et al., 2018; Förster, Downsborough, Biber-Freudenberger, Kelboro, & Börner, 2020; Gottwald & Krätzer, 2014; Grefe, 2016; Heimann, 2019; Liobikiene, Balezentis, Streimikiene, & Chen, 2019). Proponents of the bioeconomy highlight the prospects of bioeconomic innovations, to produce food, materials, and other products in a more efficient and therefore sustainable way (Geng, Haight, & Zhu, 2007). They argue that bioeconomy or eco-industrial development has the potential to provide solutions for some of the most pressing sustainability challenges including combating hunger (SDG 2), providing clean and affordable energy (SDG 7) and the fight against climate change (SDG 13) (El-Chichakli, von Braun, Lang, Barben, & Philp, 2016). Critics of the bioeconomy approach, for example, argue that an increasing reliance on biomass—for example, to substitute fossil fuel resources—has the potential to exacerbate pressures on natural resources while also accelerating biodiversity loss and land degradation in biomass supplier countries (Biber-Freudenberger et al., 2018; Escobar, Haddad, Börner, & Britz, 2018; Rajeswar, 2010). Furthermore, it is pointed out that bioeconomic growth might not be able to solve or will not even contribute to alleviate classical development challenges related, for example, to unequal societal distribution of benefits from economic activities as long as these concerns are not being properly targeted by appropriate policies (Förster et al., 2020; Kleinschmit et al., 2017).

As a result of the ongoing discussions, different bioeconomy discourses and storylines have developed (Peltomaa, 2018). The word bioeconomy itself can trigger positive as well as negative connotations depending on the specific sector of the bioeconomy, the sustainability challenge, as well as the storyline associated with different bioeconomic development strategies. Academic studies have shown that sustainability impacts are likely to mirror the diversity of and emphasis on specific bioeconomy sectors within a country (Biber-Freudenberger et al., 2018; Lyytimäki et al., 2018). Results by Biber-Freudenberger et al. (2018), for example, indicate that while countries with a focus on high-tech bioeconomies with low biomass inputs have shown sustainability gains in terms of renewable energy share and their ecological footprint between 2000 and 2015, while biomass-based bioeconomies have not been able to improve sustainability outcomes for the same indicators and time. At the same time, high-tech bioeconomies remain those with the highest consumption footprints and primary sector-based bioeconomies were able to significantly reduce undernourishment during the same period.

Considering the plethora of different national bioeconomy strategies often emphasizing different bioeconomic sectors (Dietz et al., 2018), those considering bio-economic development and growth as a transformative pathway envisaged to address current sustainability challenges need to be critically discussed based on both empirical evidence and expert judgment.

A number of complex sustainability challenges regarding public health provision, energy security, changing mobility concepts, as well as food and water security in a more and more climate-constrained world have come to the forefront of transdisciplinary sustainability science (Grin, Rotmans, & Schot, 2011; Loorbach & Rotmans, 2010; Rockström et al., 2009). Addressing these challenges requires new scientific approaches and innovative thinking and practice, which can guide grand societal shifts in production and consumption patterns and overall societal behavior toward greater sustainability (Polanyi 2001). Understanding such change as processes of transformation and transition, international scholarly literature tries to provide conceptual answers to these highly topical challenges. Related contributions conceptualize the inherent systemic connections between humans and nature (socio-ecological systems, Gunderson & Holling, 2001; Olsson, Folke, & Berkes, 2004; Olsson et al., 2006; Parsons, 2004; Smith & Stirling, 2010) and humans and our technical systems (socio-technical systems, Loorbach & Rotmans, 2010; Schot & Kanger, 2018) as two different, but interdependent systems. Established technologies are highly intertwined with user life styles and livelihoods, while both ultimately depend on healthy ecological systems (Raworth, 2012). This relationship can be described as a socio-ecological-technical system (SETS) (Geels & Schot, 2010; Göpel, 2016). Transformations thus refers to a web of processes of change created and fueled through the coevolution of economic, ecological, cultural, technological, political, and institutional developments at different scales involving numerous actors on multiple societal levels (Förster et al., 2020). This has conceptual and practical links to the field of applied bioeconomy.

Dietz et al. (2018) describe four transformation pathways for the bioeconomy including the biomass-based substitution of fossil fuels (TP1), increase of primary sector productivity (TP2), new and more efficient uses of biomass (TP3), and the development of industrial applications relying on biological principles and organisms, but without high biomass inputs (TP4). The authors highlight that the implications of implementing national policy strategies for the bioeconomy along the four pathways for achieving different SDGs would not only depend on the pathway type, but also on international and domestic factors such as markets, trade, and governance regimes (Dietz, Grabs, & Chong, 2019). For the bioeconomy, the authors argue that the associated risks are not yet comprehensively governed for leaving potential regulatory gaps and gray zones for the implementation of national bioeconomy strategies in everyday socioeconomic realities (see also Förster et al., 2020).

In order to concretize the potential risks and benefits of bioeconomic developments, we provide an analytic snapshot of the potential chances and risks of bioeconomic growth along subcategories of these pathways, which feature prominently in both scholarly and public debates. Based on expert judgment and a systematic literature review, we assess which bioeconomic innovations are more

TABLE 1 Bioeconomic sectors, associated transformation pathways, examples for technological innovations as well as most commonly discussed benefits and risks

Sector	Transformation pathway	Technology examples	Most commonly discussed sustainability benefits	Most commonly discussed risks of increased sustainability	References
Bioenergy sector (energy)	TP1: Fossil fuel substitution	Algae-based biofuels; energy crops; wood pellets; biogas, biodiesel; "green" hydrogen; cascading uses of agricultural waste.	Reducing greenhouse gas emissions and air pollution; novel energy sources for poor households; reuse of waste biomass.	Direct and indirect land use change and increased deforestation; land use competition for food and biodiversity conservation; potential health issues.	e.g., Ali & Abdulai, 2010; Azar, Johansson, & Mattsson, 2013; Creutzig et al., 2015; Immerzeel, Verweij, van der Hilst, & Faaij, 2014; Love, Einheuser, & Nejadhashemi, 2011; Mangoyana & Smith, 2011; Miyake, Renouf, Peterson, McAlpine, & Smith, 2012; Righelato & Spracklen, 2007; Varshney, Bansal, Aggarwal, Datta, & Craufurd, 2011
Food and feed sector (FoodandFeed)	TP 2: Boosting primary sector productivity TP3: New and more efficient biomass uses	GMOs for food and feed production; organic farming; ecological intensification; integrated pest management; vertical farming; rooftop farming; insects as a protein source for food and feed production.	Highly dependent on specific innovation; increasing food production and lower production costs (e.g., GMOs); less pesticides; less impacts on biodiversity; more income and lower vulnerability to impacts of climate change of farmers.	Highly dependent on specific innovation; inbreeding with wild relatives; negative impacts on biodiversity and ecosystem services; health risks, for example, due to use of pesticides; increasing competition for smallholder farmers; unequal access to education, knowledge, and technology; concentration of benefits on high-tech. Lower yields and food security (e.g., organic farming); production sectors and highly skilled workforces; exclusion from technical processes.	e.g., Benbrook, 2012; Bommarco, Kleijn, & Potts, 2013; Buehler & Junge, 2016; Cook, Khan, & Pickett, 2007; Fan, 2009; Guimapi et al., 2020; Kleijn et al., 2019; Klümper & Qaim, 2014; Kogan, 1998; Kremen & Miles, 2012; Kwon & Kim, 2001; Meemken & Qaim, 2018; E. D. Perry, Ciliberto, Hennessy, & Moschini, 2016; Qaim, 2009; Titttonell, 2014; Titttonell & Giller, 2013; Tsatsakis et al., 2017; Varshney et al., 2011; Vercillo, Kuuire, Armah, & Luginaah, 2015; Wanjiku Kamau, Biber-Freudenberger, Lamers, Stellmacher, & Borgemeister, 2019; Webersik & Wilson, 2009; Wright & Kurian, 2010
High-volume biomass-based sector—	TP 1: Fossil fuel substitution	Bioplastics and other bio-based materials for the construction;	Reducing greenhouse gas emissions and pollution; generation of livelihood	Direct and indirect land use change and increased deforestation;	e.g., Brodin, Vallejos, Opedal, Area, & Chinga-Carrasco, 2017; Colwill, Wright,

TABLE 1 (Continued)

Sector	Transformation pathway	Technology examples	Most commonly discussed sustainability benefits	Most commonly discussed risks of increased sustainability	References
Manufacturing (HighVol)	TP3: New and more efficient biomass uses	textile or packaging industry.	opportunities and income sources for farmers; emerging value chains in bioplastic and biochemical sectors; improved biodegradability; improved circularity and reduced ecological impact.	competition with food production and biodiversity conservation; limited biodegradability of certain bioplastics in industrial, soil, or marine environments.	Rahimifard, & Clegg, 2012; Dietrich, Dumont, Del Rio, & Orsat, 2017; Escobar et al., 2018; Partey, Sarfo, Frith, Kwaku, & Thevathasan, 2017; Philp, Bartsev, Ritchie, Baucher, & Guy, 2013; Piemonte & Gironi, 2011
The low-volume biomass-based sector—Biotechnology (LowVol)	TP 4: Low-bulk and high-value applications	Bacteria-based production and plant engineering lab-based techniques for drug and materials development; biosensors for disease protection; GMOs (not for food and feed production); biomimicry.	High economic value addition with low biomass inputs; less pollution and higher biodegradability of products; increasing level knowledge and skills due to knowledge- and technology-intensive sector requirements; health benefits due to medical applications and targeted medicine.	Unequal access to education, knowledge, and technology; concentration of benefits on high-tech. Production sectors and highly skilled workforces; increasing inequality between poor and rich within and between countries; health and ecological risks through improper use of technologies.	e.g., Aguilar, Bocheureau, & Matthiessen, 2010; S. B. Banerjee, 2003; M. Banerjee, Siddique, Dutta, Mukherjee, & Ray, 2012; Brokowski & Adli, 2019; Förster et al., 2020; Gavrilescu & Chisti, 2005; Moses & Goossens, 2017; Munshi & Sharma, 2017; Nogrady, 2018; Singer & Daar, 2001
Waste sector (waste)	TP3: New and more efficient biomass uses	Reuse of waste for bioenergy, for example, biogas, food or feed production, for example, proteins from insects using waste as feedstock.	Lower resource inputs due to circular economy; less pollution due to improved cascading use systems; waste management and higher recycling rates; benefits in terms of energy provisioning and food security, for example, using waste as feedstock or manure for insects or algae.	Unintended market effects by using previously underutilized resource having negative ecological impacts; health and ecological issues, for example, through accumulation of harmful substances such as heavy metals in organisms and soils.	e.g., Leslie, Leonards, Brandsma, de Boer, & Jonkers, 2016; Mosquera-Losada et al., 2017; Olofsson & Börjesson, 2018; Razza, D'Avino, L'Abate, & Lazzeri, 2018; Zink & Geyer, 2017

associated with benefits and which are more linked to risks. For this, we distinguish between different SDGs and analyze which factors underlay the judgment of experts and outcomes of studies.

Other studies have assessed the expectations of a growing bioeconomy for the SDGs such as El-Chichakli et al. (2016), Issa, Delbrück, and Hamm (2019) and Heimann (2019). This is the first study that assesses the chances and risks of specific bioeconomic transformation pathways combining expert opinions and scientific literature.

2 | MATERIAL AND METHODS

2.1 | Conceptual framing of bioeconomy

We define bioeconomy as comprising economic sectors, which utilize biological resources, principles, or processes to create products, goods, and services. This includes directly and indirectly bio-based sectors such as forestry or agriculture and, respectively, biopharmaceutical and cosmeceutical products, chemistry (e.g., bioethanol, lubricants, biofertilizer),

energy and mobility (e.g., bioelectricity, biofuels) or the construction, packaging and manufacturing sector (e.g., bioplastics), as well as waste management (e.g., bio-based applications for waste water treatment and solid waste recycling). To facilitate our analysis below, we categorize these sectors into five blocks: 1. bioenergy; 2. food and feed; 3. high-volume bio-based production and manufacturing; 4. low-volume biotechnology sector; and 5. waste while relating them to the most commonly discussed benefits and risks (Table 1). As described before, according to Dietz et al. (2018), change in these sectoral blocks can occur along four transformation pathways (TP), which we refer to in the detailed description of the bioeconomic sectors (Table 1 and Data S1).

2.2 | Literature review

A literature review was conducted on Web of Science following a systemized search term selection for each combination of SDG and bioeconomic sector. For each SDG/Sector Combination, a term was created following the pattern *Sector+SDG+bioeconomy* (Data S2). The publications for the literature review were selected between May and August 2017. Publications before 2010, reviews, and editorials were excluded from further analysis.

Only papers satisfying the following criteria were selected for further analysis:

- 1 A new technology/innovation is being suggested
- 2 The new technology is bio-based (depends on organisms but not [only] on machines or techniques)
- 3 The positive or negative implications for SDGs are being discussed

The selection of these papers was based on the review of the title and the abstract. Based on the defined criteria, a total of 946 publications were selected for this study. These studies not necessarily had to mention the SDG but describe their research output in the context of a sustainability aspect that we could relate to one or more SDGs. An overview of all selected publications and their evaluation can be found in Data S3 and S4. For the long-term trend analysis of publication numbers per sector since 1945, the sector search term was combined only with the bioeconomy search term (*Sector+bioeconomy*, Data S2). For this analysis, publications and their abstracts did not undergo any screening process but trend analysis relied merely on the total numbers of publications found for each search term per year in Web of Science.

2.3 | Questionnaire

Similar to the literature review, we also evaluated expert's opinions on the impact of different bioeconomy sectors on the SDGs. A link to a questionnaire was sent to different professional networks professionals working on sustainability and transformation issues such as the Sustainable Development Solutions Network (SDSN), the Sustainability Transitions Research Network (STRN), the Biodiversity and Ecosystem Services Network (BESNet), or the pan-African expert network on food

and non-food biomass (BiomassNet). We purposely spread our questionnaire as much as possible to have high number of respondents from different countries and sectors all over the world. Each expert was asked to select up to three SDGs he or she felt most informed about and to judge how a growing bioeconomy in five different sectors would affect the selected SDGs. A total of 200 self-selected experts answered the questionnaire. After the deletion of duplicates and invalid responses, we retained responses of 184 experts of which 20 assessed only one, 16 assessed two, and 148 assessed three different SDGs. As each expert was asked to evaluate impacts of each SDG on five Bioeconomic sectors 2,480 single assessments were recorded for analysis (Data S5).

2.4 | Data analysis and visualization techniques

Literature review and questionnaire results were analyzed using visual interpretation of sunburst diagrams and by calculating the level of agreement as the inverse value of *unlikability* (Kader & Perry, 2007; M. Perry & Kader, 2005):

$$u = 1 - \sum p_i^2,$$

where $p_i = \frac{k_i}{n}$ and u corresponds to the share of comparisons which are unlike. The inverse value of *unlikability* is a measure of agreement as it is the inverse value of the measure of diversity as originally defined by Greenberg (1956) and introduced later as a measure for the variability of categorical variables (Kader & Perry, 2007; M. Perry & Kader, 2005). The smaller the value of *unlikability*, the higher the value of agreement (less variation). In our analysis, we used the inverse value of *unlikability* as a measure of agreement and the number of publications or experts served as a measure of robustness in each SDG outcome or sectorial category.

Questionnaire and literature review data were analyzed using the statistical computing environment R. Sunburst diagrams were generated using the package *sunburstR* (Bostock, Rodden, Warne, & Russell, 2019) and maps were generated using the package *rworldmap* (South, 2011). Additional packages used for visualization are *ggplot2* (Wickham, 2016), *ggrepel* (Slowikowski, 2019), *RColorBrewer* (Neuwirth, 2014), *magick* (Ooms, 2018), and *cowplot* (Wilke, 2019). Packages that were used for data wrangling and analysis are *dplyr* (Wickham, François, Henry, & Müller, 2019), *tidyr* (Wickham & Henry, 2019), *tidyverse* (Wickham, 2017), *reshape* (Wickham, 2007), *rlist* (Ren, 2016) and *ragree* (Redd, 2019).

3 | RESULTS

3.1 | Overall sustainability impacts of bioeconomy according to experts and scientific literature

Our analysis of the literature review results showed that most of the studies analyzed data on a global scale and had no specific

geographical focus. These studies tended to have a rather positive outlook on bioeconomy irrespective of the sector (Figure 1a,b and 2a). Studies with a focus on the national or local scale found more negative and context-specific impacts but focused mainly on the bio-energy and the food and feed sector. For Europe, south-east Africa, south-east Asia, Oceania and most parts of Southern and Central America, we found only very few, or no studies at all that focus on northern Asia and most parts of northern and central Africa indicating major research gaps in those areas.

The distribution of studies as well as expert responses across countries shows that most experts as well as studies on the topic of bioeconomic growth focus on India and Brazil (Figure S1). Also, China, the United States, and Ethiopia are relatively often within the focus of scientific publications on bioeconomic developments. Compared to the distribution of publications, questionnaire responses were even more clustered (Figure 1b). While we received a large number of responses from the United States, western and northern Europe, West Africa (Nigeria, Cameroon, and Ghana), East Africa (Ethiopia and

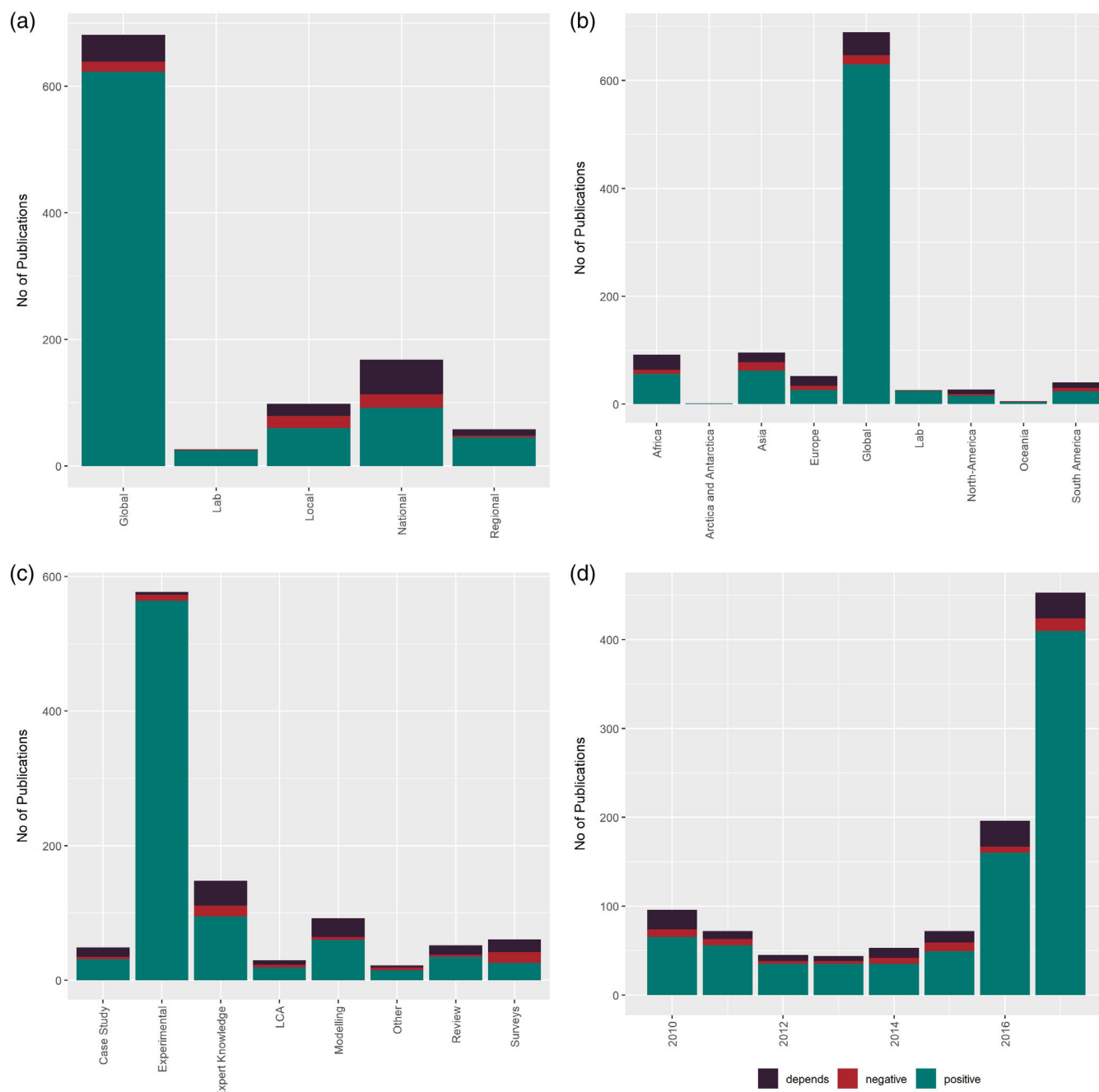


FIGURE 1 Number of Publications investigating the positive, negative, and context-dependent impacts of bioeconomic growth on sustainable development split by the spatial scale (a), the focus continent (b), the applied methodology (c), and the year of publication of their study [Colour figure can be viewed at wileyonlinelibrary.com]

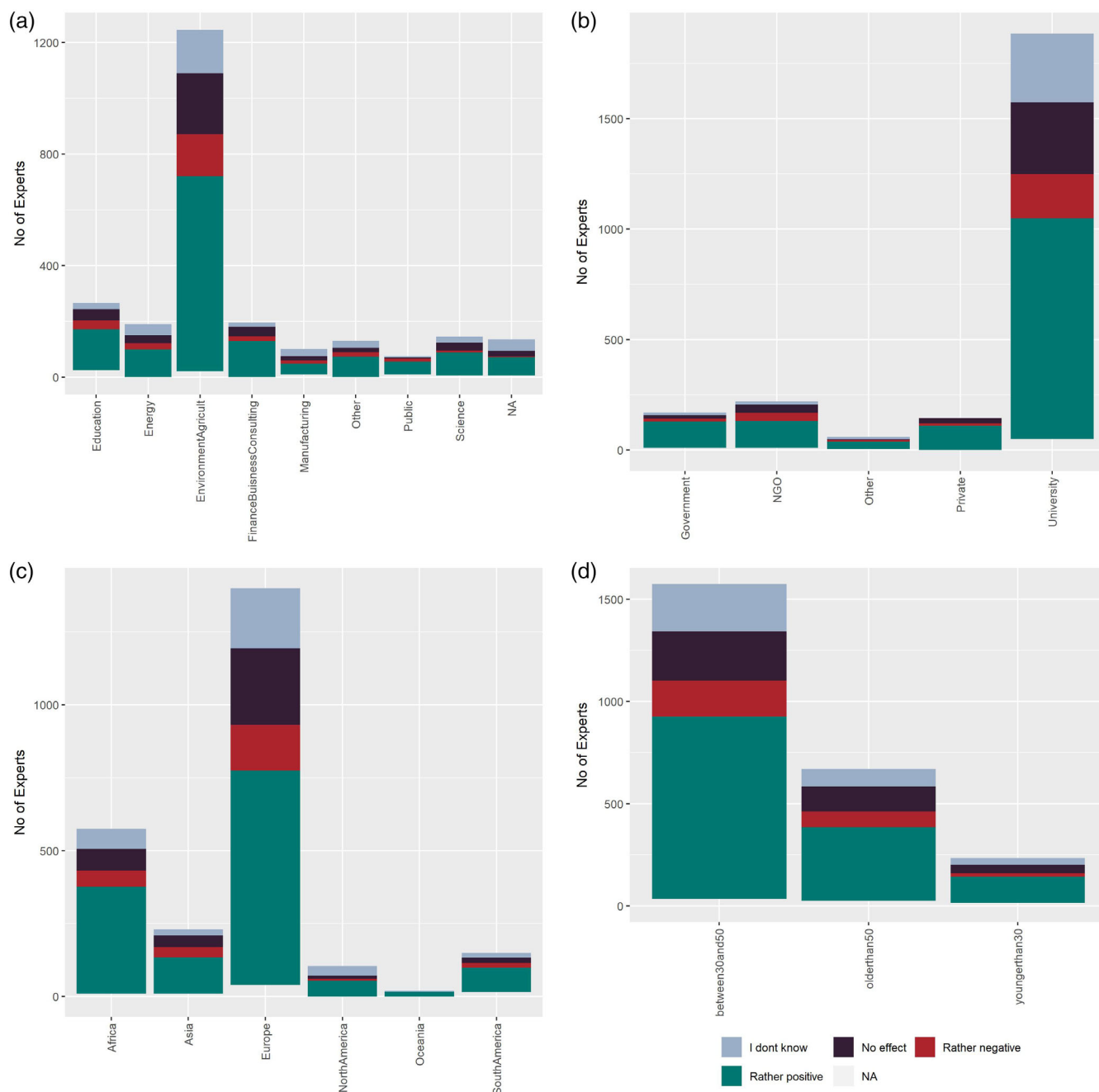


FIGURE 2 Number of expert questionnaire responses assessing the impacts of bioeconomic growth on sustainable development split by the work sector (a), the employer type (b), the working continent (c), and the age of the respondent. Please note that experts were asked to assess the impacts of five different sectors on up to three different SDGs leading to a higher number of expert responses than number of experts involved (200) [Colour figure can be viewed at wileyonlinelibrary.com]

Kenya), Chile, Iran, and Indonesia, we did not record any responses from most parts of Northern and Central Africa as well as Central Asia. The overlap between the study's focus countries and the expert working countries indicates that a lack of studies and experts are uniformly distributed and that a research and expert knowledge gap was not a result of the study design.

Overall, there has been an increasing trend of publications about the impacts of bioeconomy on the SDGs, especially since 2013. Looking at the share of publications across different sectors and its

trend since 1945, we find that trends oscillated before 1990 without clear trends. Since then, however, we find an increasing trend for publications on bioenergy and waste, a decreasing trend for publications on the low-volume biomass-based sector and a stagnation of publications about innovations in the food and feed sector, and about the high-volume biomass-based sectors (Figure S2). Analysis of publication numbers since 2010 that were subjected to our selection protocol (see Material and Methods) shows that while the total share of findings supporting positive or negative impacts did not vary

considerably over the years (Figure 1d), we found a steady increase in the of research focusing on the waste, the low- and the high-volume biomass-based sectors (Figure S3).

Our results show that most studies with an experimental design (which were by far the most prominent study types) highlighted mainly positive impacts of all bioeconomic sectors while research based on expert knowledge, surveys, and modeling were much more critical in their assessment (Figure 1c). This suggests that those studies that due to their study design are more focused on direct and anticipated impacts are less likely to detect unintended and often negative secondary impacts that only become visible at the system scale. These effects, which often manifest themselves only after new technologies were scaled up to higher levels, are more likely to be captured by research methods focusing on socio-economic and ecological system behavior such as surveys and expert knowledge. This is also supported by the finding that experimental studies were conducted for all bioeconomic sectors while studies based on expert knowledge, surveys, and modeling approaches were mainly focusing on sectors that have provided technologies, which were scaled up to larger scale such as bioenergy and the food and feed sector (Figure S3).

For the Questionnaire data, we found that most experts were employed by the environmental or agricultural sector and fewer experts considered themselves as employees of the other sectors (Figure 2a). While members of other sectors were much less critical toward growing bioeconomic sectors, members of the environmental and agricultural sector were more considerate of potential negative impacts or their contextual dependencies. This was also true for university employees, which formed the majority of the respondents (Figure 2b). Employees of private companies and the government were less likely to point out potential negative impacts. This suggests that companies, which often have a strong interest in promoting bioeconomic products and services, and governmental employees, which are might be biased toward endorsing bioeconomic policies, are more likely to focus on positive aspects of bioeconomic transformation, whereas university employees, in particular, those working in the environmental and agricultural sector are more likely to discuss potential negative impacts.

Our survey was mostly answered by employees of a European organization, institution, or company but also people working in Africa reached a relatively high number (Figure 2c). In terms of responses, Europeans by tendency seem to have a more critical attitude toward bioeconomic growth than Africans. Most respondents were between 30 and 50 years old, whereas only few were younger than 30 years. While we did not find much of a difference in response behavior between 30–50 and older than 50-year-old respondents, we found much less critical assessments of bioeconomic impacts for respondents younger than 30 years. We attribute this variation of attitude to the lack of bioeconomic policies in Africa compared with the relative mature states of bioeconomic policies in many European countries, where negative consequences have been studied in more countries (compare Figure S1) and as a consequence policies have become more

considerate of potential risks of bioeconomic growth than in most African countries (compare Dietz et al., 2018).

3.2 | SDG specific bioeconomy impacts according to experts and scientific literature

While we found many studies focusing on health and wellbeing (SDG3, $n = 121$), clean water and sanitation (SDG 6, $n = 102$), life below water (SDG14, $n = 102$), and life on land (SDG15, $n = 102$), we found very few looking at the impacts of bioeconomy on peace justice and strong institutions (SDG 16, $n = 3$), reduced inequalities (SDG 10, $n = 10$), industry, innovation and infrastructure (SDG9, $n = 16$), and quality education (SDG4, $n = 19$). Additionally, literature on bioeconomic growth and SDGs tended to be relatively balanced between the different sectors for SDGs related to nutrition and human health (SDG 2,3 and 6) as well as those related to sustainable lifestyles (SDG 11, 12, and 13) and biodiversity impacts (SDG 14 and 15) compared with SDGs focusing on aspects of equality (SDG 1, 5, 10), education (SDG 4 and 8), and governance (SDG 16 and 17). For the latter, literature focused mainly on the sectors bioenergy and food and feed. This result highlights major research gaps regarding potential unintended secondary impacts of bioeconomic growth, in particular for the high- and low-volume biomass-based sectors as well as the waste sector (Figure S4).

Most experts selected Climate Action (SDG13, $n = 80$), Zero Hunger (SDG 2, $n = 73$), and Affordable and Clean Energy (SDG7, $n = 55$) as their core expertise. Very few experts selected Peace, Justice, and Strong Institutions (SDG 16, $n = 3$), Life below Water (SDG 14, $n = 5$), and Partnership for the Goals (SDG 17, $n = 5$). As each expert was asked to assess all bioeconomic sectors for the individually selected SDGs, the same amount of responses was recorded for all bioeconomic sectors within each SDG (Figure S5).

Results of the literature review and questionnaire indicate mixed findings and considerable research and knowledge gaps specific for SDGs and bioeconomic sectors (Figures 3 and 4, Figures S4 and S5). For example, we found no studies looking at the impact on gender equality (SDG5) from the waste sector or the low-volume biomass-based sector (Figure 3). Here, we focus our discussion on five SDGs, namely No Hunger (SDG2), Good Health (SDG 3), Gender Equality (SDG 5), Climate Action (SDG 13), and Life on Land (SDG 15), which were frequently selected by experts and the focus of scientific studies while also exemplifying different dimensions of sustainability (find sunburst diagrams for all SDGs in Figures S4 and S5).

Most publications indicate rather positive outcomes for different SDGs and growth in different bioeconomic sectors. This is especially true for the fight against hunger (SDG2), the promotion of good health (SDG3), and climate action (SDG 13). Expert opinions are showing a similar pattern although a relatively high number of experts are also expressing their uncertainty especially about the impact on the fight against hunger (SDG2), gender equality (SDG 5), and climate action (SDG 13).

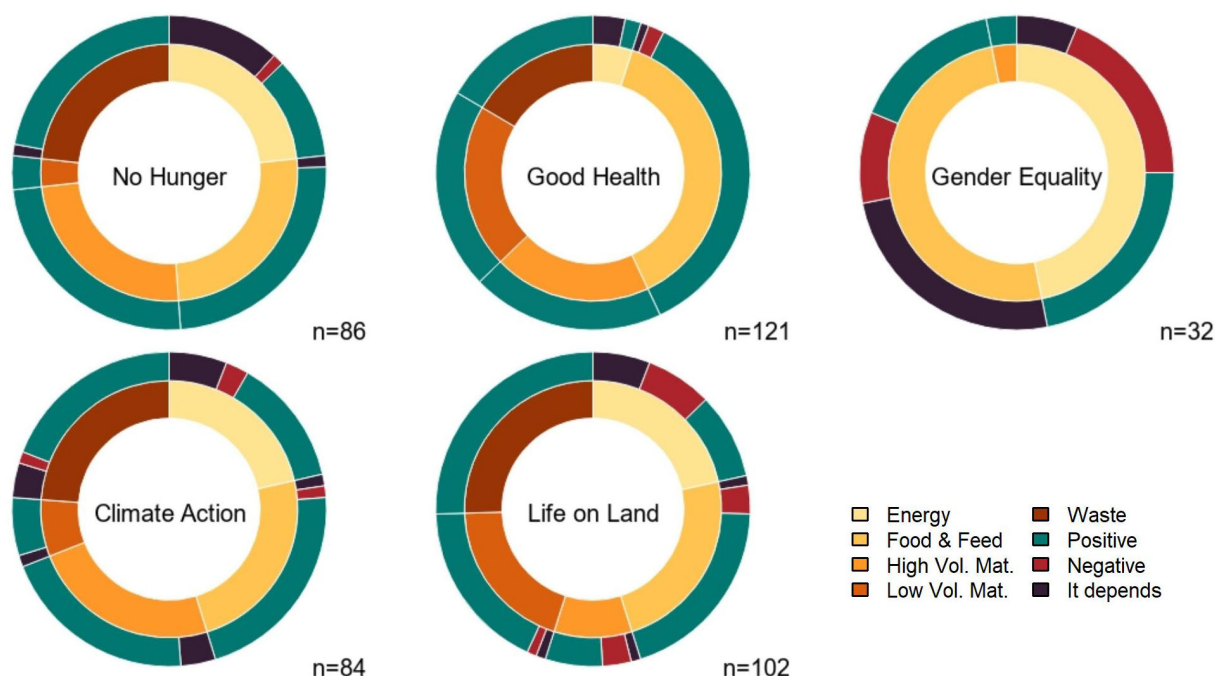


FIGURE 3 Selected sunburst diagrams of literature review results. While the inner circle represents the different bioeconomic sectors (and transformation pathways), the outer circle indicates the sustainability judgment put forward in the scientific publication. Sunburst diagrams for all SDGs are available in the Supplementary Material [Colour figure can be viewed at wileyonlinelibrary.com]

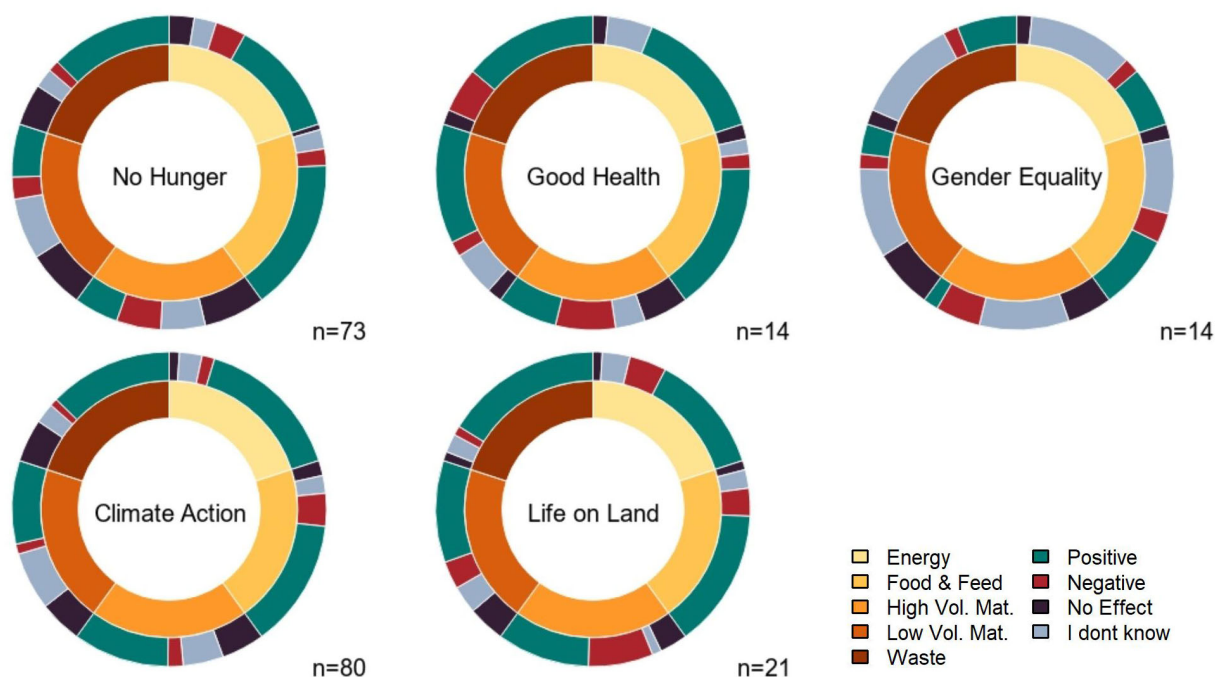


FIGURE 4 Sunburst diagrams of expert questionnaire results. While the inner circle represents the different bioeconomic sectors (and transformation pathways), the outer circle indicates the results of the expert response. Sunburst diagrams for all SDGs are available in the Supplementary Material [Colour figure can be viewed at wileyonlinelibrary.com]

For the promotion of gender equality (SDG 5) and the conservation of life on land (SDG15), we found a higher proportion of publications highlighting the negative or context-dependent consequences. This is especially true for the bioenergy sector, which, according to

reviewed publications, is more likely to have a negative impact on sustainability in each dimension including the fight against hunger. Innovations from the food and feed sector also seem to be more likely having negative impacts on the reduction of poverty (SDG1) and

inequality in general (SDG10) and among men and women (SDG5), while fewer negative consequences are expected for the other SDGs. This result is in line with our previous argument that negative consequences of sectors that have been scaled up to higher levels are more likely to be captured by scientific literature. Innovations from the waste, the low- and the high-volume biomass-based sectors have been less frequently studied, in particular with regard to social impacts such as gender equality.

Among experts, we found a relatively high confidence in the positive impacts especially of the bioenergy as well as the food and feed sector (Figure 4). This is in particular true for the fight against hunger (SDG2), the promotion of health (SDG3), climate action (SDG 13), and the conservation of life on land (SDG 15). Few experts do not expect any impact on certain SDGs from bioeconomic growth.

At the same time, we found a high uncertainty regarding the positive or negative impacts on sectors such as high-volume biomass-based materials and low-volume biomass-based materials in particular for the fight against hunger (SDG2), the promotion of health (SDG3) and gender equality (SDG5), as well as climate action (SDG13). Most negative impacts are expected from the high-volume biomass-based sector for the conservation of life on land (SDG15). This shows a high uncertainty regarding the impacts of growing demands on land and biomass from agriculture and food as well as other biomass-intensive bioeconomic sectors (here excluding the bioenergy sector).

Based on certainty analysis as a combination of robustness and agreement of findings, we highlight different research gaps and unresolved issues for literature results as well as questionnaire findings (Figure 5, Tables S1 and S2). For the impacts of the food and feed sector on health (SDG3), we found most publications also with a relatively high level of agreement indicating a *well-established* connection. At the same time, we found most assessments of the impacts of most bioeconomic sectors on most SDGs within peer-reviewed journals to be *established but incomplete* (high agreement but low number of publications). This is in particular the case for studies on the impact of high-volume biomass-based sectors on poverty (SDG 1), gender equality (SDG 5), and the promotion of sustainable cities (SDG11) and low-volume biomass-based sectors on the promotion of education (SDG 4), decent work (SDG8), the fight against hunger (SDG2), and inequalities (SDG11). Only findings of publications assessing the impact of the food and feed sector on poverty (SDG 1) remain *unresolved* as a number of publications were found but with a relatively low level of agreement. Knowledge gaps are highlighted by *inconclusive* connections between SDGs and bioeconomic sectors including energy and the conservation of life on land (SDG 15), the fight against poverty (SDG1) and the promotion of gender equality (SDG 5) as well as the impact of the food and feed sector on gender equality (SDG5).

These results support our previous findings that research on established bioeconomy sectors such as bioenergy and the food and feed sector is more abundant but also more diverse in its findings. This suggests that negative impacts for these sectors have become more apparent in studies in particular those looking at complex sustainability issues such as poverty (SDG1) and as a result a more

balanced discussion has established among the scientific community. Other sectors, in particular the low- and high-volume biomass-based as well as the waste sector, which have been discussed less in scientific literature, show by tendency a higher level of agreement. This might be due to the generally lower impacts these sectors might have or due to the fact that they have not been scaled up as much as innovations from the bioenergy or the food and feed sector and the limited number of studies looking at different sustainability impacts.

Similar to the literature results, certainty analysis of expert questionnaire findings indicate either *established but incomplete* or *inconclusive* results for the impacts of bioeconomic sectors on most SDGs. However, we find a higher number of *inconclusive* assessments for a different SDGs and bioeconomic sectors compared with the literature review results. Among those, our analysis revealed lowest reliability for findings about the impact of bioeconomy on the promotion of global partnerships (SDG 17), decent work (SDG 8), the reduction of inequalities (SDG10), the promotion of health (SDG3), and gender equality (SDG5). Lowest agreement was found for the high-volume and low-volume biomass-based sectors. Lowest agreement in combination with low reliability was found in particular for the contribution of the high-volume biomass-based sector to decent work (SDG8) and the reduction of inequalities (SDG 10). *Established but incomplete results* were found in particular for the promotion of peace and justice (SDG 16) through the high- and low-volume biomass-based sectors, the conservation of life below water (SDG 14) and the promotion of decent work (SDG 8) through the waste sector and the development of industry and infrastructure (SDG 9), and the promotion of education (SDG4) and decent work (SDG 8) in combination with the energy sector.

Well established results were found for few combinations of bioeconomic sector and SDG including, the impact of the food and feed sector on the fight against hunger (SDG2), the impact of the energy sector on climate action (SDG 13), and the provision of affordable energy (SDG7). For the same SDGs and the remaining bioeconomic sectors, we found *unresolved* connections in particular about the impacts of the high- and low-volume biomass-based sectors as well as the bioenergy sector on climate action (SDG13), the fight against hunger (SDG2) and the provisioning of clean energy (SDG7).

While literature capturing almost a decade of scientific debate highlights mostly positive sustainability impacts of upcoming bioeconomic sectors (e.g., waste, low- and high-volume biomass-based sectors), our snapshot of current expert opinions seems to be representative of uncertainties regarding the potential negative impacts of new upcoming bioeconomic innovations from the low- and high-volume biomass-based sector on climate action (SDG 13), the fight against hunger (SDG 2), and the provision of clean energy (SDG 7). Although experts frequently selected these SDGs, agreement is rather low among them. For other SDGs such as the promotion of peace and justice (SDG 16), the conservation of life under water (SDG 14) and inclusive economic growth (SDG 8) only few experts assessed the impacts of these new upcoming sectors in particular of waste and low-volume biomass-based bioeconomic innovations. Despite a relatively high level of agreement among them, their assessment can only

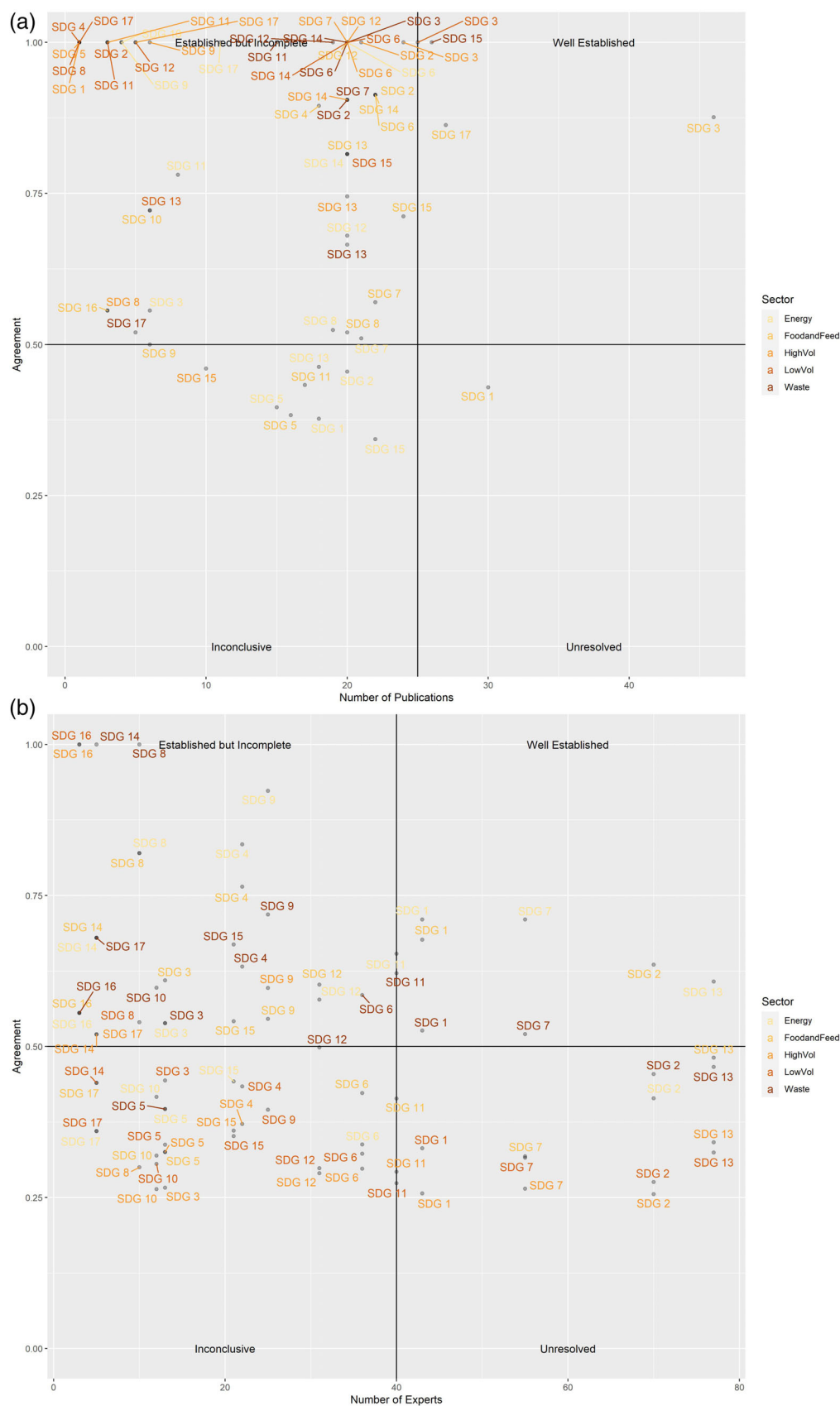


FIGURE 5 Certainty analysis as a measure of agreement and robustness of literature review (a) and questionnaire results (b) for the sustainable development goals (SDGs, see label) and the bioeconomic sectors (see color code). The number of publications respectively experts is considered as an indicator of the robustness of results while the level of agreement reflects the inverse value of variability among opinions and research results. An increase in robustness (number of experts or publications) as well as agreement increases the certainty of the findings [Colour figure can be viewed at wileyonlinelibrary.com]

be considered incomplete as only very few experts felt comfortable answering our questions about the impact of these new upcoming bioeconomic sectors on the conservation of life below water (SDG 14), the support of peace, justice, and strong institutions (SDG 16), and the promotion of decent work and economic growth (SDG 8).

Overall, our results point out that according to scientific literature predominantly positive sustainability impacts from new and upcoming bioeconomic innovations are expected. This is also the case for other bioeconomic sectors such as bioenergy and the food and feed sector, but here, we also find studies pointing out the negative expected impacts in particular on SDGs, which are likely to be subject to indirect negative impacts such as equality and inclusiveness. This is also supported by our findings that in particular those studies with system approaches, for example, case studies and expert interviews, which are by nature more considerate of indirect impact pathways, are more likely to point out potential negative indirect impacts. Studies using these more inclusive methods looking at social sustainability and related SDGs are, however, lacking for upcoming bioeconomic innovations from the waste, the low- and the high-volume biomass-based sectors.

4 | DISCUSSION AND CONCLUSIONS

We comparatively assess evidence and views on the contribution of bioeconomic growth to sustainable development in the scientific literature and among a global sample of experts. Overall, we find positive expected outcomes to dominate especially in the literature, but the reliability of evidence and agreement among experts and scientific literature vary considerably across sectors of the bioeconomy and SDG dimensions.

The academic literature tends to focus on direct and often desired impacts of bioeconomic growth while indirect and potentially undesirable impacts are more frequently purported in expert responses. Correspondingly, technical or natural scientific studies using experimental approaches tend to support claims about the beneficial impacts of bioeconomy, whereas social science motivated studies, including case studies and survey-based research, are by design more suitable to capture indirect social impacts and thus more often highlight negative or context-dependent outcomes.

Overall, we find that positive sustainability impacts from bioeconomic innovations, which have been scaled up to higher levels, such as biofuels and the food and feed sector, are more disputed within scientific literature compared with other sectors. We argue that this is a result of innovations being subject to different stages of typical technology hype cycles. According to Gartner Inc. (2019), these hype cycles typically follow a pattern where expectations increase dramatically triggered by a new technology. Often success stories are being developed and promoted through scientific publications demonstrating the value of the innovation. After the technology has been scaled up, however, limitations and possible negative tradeoffs become apparent leading to a steep decrease of expectations and to the so-called trough of disillusionment. Gartner Inc. (2019)

found that, after a while, the expectations rise again to a moderate level when tradeoffs and negative impacts are considered and reflected by second and third generation innovations. The hype cycle narrative has been used and studied in the context of bioeconomy by other studies such as Stern et al. (2018), Alkemade and Suurs (2012), Rajeswar (2010), or Clark et al. (2018).

According to our results, expectations for young innovations, for example, in the low-volume biomass-based sector, are likely to be in the peak phase of expectations with multiple publications pointing out their potential direct benefits. Other bioeconomic sectors such as biofuel and many food and feed innovations tend to have passed the trough of disillusionment thus reaching a plateau of realistic expectations considerate of its limitations and tradeoffs. It is a well-documented phenomenon that scientific debates about the social, economic, or ecological impacts of new technologies follow a paradigmatic course (Kuhn, 1962; Kuhn & Hacking, 2012). While positive views usually dominate the early phases of scientific dialogues highlighting the beneficial outcomes of new technologies, it takes time until the society-wide, complex, and unexpected consequences caused by the introduction of new technologies become visible. Over time, therefore, scientific discourses about new technologies become not only more nuanced but also more contested. Within the field of the bioeconomy, especially the debate about the sustainability of biofuels has reached a more advanced debate stage (Alkemade & Suurs, 2012), in which, it becomes increasingly apparent that the beneficial outcomes of new technologies only materialize when specific socio-economic and political prerequisites are in place. The same is true for innovations related to bioenergy from the forestry sector for energy and paper products, which according to a study by Stern et al. (2018) are likely to decline in the future. Our analysis of both the expert views and the secondary literature has shown that for certain sectors of bioeconomic transformation, which have been scaled up, we are seeing a controversial debate about the positive and negative impacts. For other sectors, with new and upcoming innovations, we also expect according to Gardner et al. to see the rise of a complex and controversial debate after the point of inflated expectations has been reached.

Our study has different limitations that should be considered when interpreting the results. The literature review only considers publications since 2010 and not before. Depending on the bioeconomic sector, this time window might be the reason why either positive or negative findings were more prominent. Discussions about the positive and negative aspects of the bioenergy and the food and feed sector, for example, might have been more prominent in the scientific literature before 2010. Additionally, we used a keyword-based systematic literature review without considering additional literature. As any other systematic literature review dealing with a similar complex topic, we are likely to have missed some important studies that would have fulfilled our selection criteria. We are, however, confident that the literature we considered provides a good and unbiased sample of the existing scientific output and its focus. Similar to the literature review, our findings based on the expert questionnaire should be interpreted considering a potential self-selection and distribution bias

as we distributed the questionnaire among members in expert networks on sustainable development and bioeconomy. Additionally, each expert-based SDG-bioeconomy assessment cannot be considered as independent expert judgments, as each expert was asked to assess risks and benefits for five sectors and three SDGs.

Even with these limitations, our study provides an overview of current scientific understanding, expert opinions, and concerns and, more importantly, the existing knowledge gaps and uncertainties related to the costs and benefits of a growing bioeconomy. Despite opportunities for positive impacts of bio-based transformation, especially on key development goals, such as SDG 2, uncertainties, risks, and disagreement among scientists and practitioners should not be ignored, but rather inform the design and implementation of bioeconomy strategies at all administrative levels. In line with Rajeswar (2010), our findings suggest that sustainability gains of new technologies tend to be overestimated, whereas complex and eventually negative impact pathways are notoriously underexplored in early stages of innovation. Technology optimists typically counter that overregulated innovation systems may stifle much needed technological progress, but this is no excuse for a lack of scrutiny in technology impact assessments. Clearly, the "...contextualization of knowledge in time and place and its connectedness to society..." (Rajeswar, 2010, p. 250) is necessary for sustainable development. In the context of a globalized bioeconomy, this involves mainstreaming sustainability risk appraisals in technology impact assessments across SDG dimensions and relevant application contexts.

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