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Learning, knowledge, and the role of government: a qualitative system dynamics analysis of Andalusia's circular bioeconomy

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Abstract. The transition from a linear bio-based economy to a sustainable circular bioeconomy depends not only on the skills that the different actors of the innovation system can find, develop, and exploit internally, but also on the efficiency with which they can access external sources of knowledge and skills related to technologies and markets. In this scenario, understanding the dynamics of learning and knowledge accumulation acquires greater importance due to the bioeconomy's position at the confluence of several technological areas. Therefore, for this study, we apply qualitative system dynamics modelling methods to the analysis of Andalusia's circular bioeconomy, obtaining important insights into its complexity due to the existence of non-linear processes, multiple feedback loops, and time delays. The models thus generated led to the identification of 20 key intervention points where targeted actions by governments and other actors could help overcome the pervasiveness of information asymmetry in the sector.

Keywords: bioeconomy, system dynamics, knowledge, innovation systems, government.
JEL Codes: O1, O2, O3.

1. INTRODUCTION

A common feature observed in government strategies for the development of a bio-based economy is the belief that a strong innovation system will play a key role in the realization of the sector's potential. In this context, the dynamics of learning and knowledge accumulation is critical and presents a key challenge as the bioeconomy is largely composed of companies with persistently low levels of digitalization (Bacco et al., 2019) and struggling to develop effective business models (Reim et al., 2019). For over 30 years, the innovation systems approach (Lundvall, 1992; Nelson, 1992) has provided an important theoretical framework to explain the complex interactions that take place between the different participants of the innovation process as well as the basis for policymaking in the fields of science, technology, innovation, and economic development. This concept has enjoyed vast popularity for the many advantages that it offers over the traditional linear models developed in the previous four decades. However, the inner dynamics of innovation systems remain somewhat unexplored, largely because innovation studies have often pursued a linear thinking approach while the innovation process is known to follow non-linear paths and involve feedback loops across all the stages.

On the other hand, while a significant share of publications and government strategies consider the bioeconomy as being intrinsically sustainable (Global Green Growth Institute, 2020; Motola et al., 2018), various experts have expressed concerns that a linear business-as-usual approach to the bioeconomy can have negative impacts if the principles of a circular economy are not followed (Bosch et al., 2015; OECD, 2014; Pfau et al., 2014; Philp, 2018; Reim et al., 2019). In response to these discussions, the term "circular bioeconomy" was created, and some attempts have been made to define the concept but clear guidance for bioeconomy practitioners is still needed (Stegmann et al., 2020). A circular economy aims to maintain the value of products, materials, and resources as much as possible while minimising the generation of waste (European Commission, 2015), thus requiring interactions across several domains and the involvement of multiple players. However, despite this complexity, most of the analyses conducted until very recently have addressed the processes and components of innovation systems for the development of a circular bioeconomy in isolation. This is changing through the application of system dynamics modelling tools.

The system dynamics modelling approach was created during the late 1950s and early 1960s to understand the non-linear behaviour of complex systems and build models that capture their dynamic nature over time (Forrester, 1961; Meadows, 2009; Sterman, 2000). It provides powerful tools to examine cause-and-effect relationships, feedback mechanisms, non-linear effects, time delays and, accordingly, high complexity. Applications of system dynamics are increasingly found in a wide range of areas, including manufacturing, construction, infrastructure, software development, healthcare, population studies, waste management, water resources management, ecological and economic systems, and environmental management, among many others (Andersson et al., 2002; Biroscak et al., 2014; Elsawah et al., 2017; Guo et al., 2001; Hakim et al., 2016; Hsieh and Chou, 2018; Ketzer et al., 2020; Kim and Andersen, 2012; Lai et al., 2017; Layani et al., 2021; Linnéusson, 2009; Magalhães et al., 2018; Mahato and Ogunlana, 2011; Oriama and Pyka, 2021; Papachristos, 2019; Phan et al., 2021; Pitoyo et al., 2018; Sahin et al., 2017, 2018; Soydan and Oner, 2012; Stave, 2010; Stave and Kopainsky, 2015; Walz et al., 2016; Zhou and Liu, 2015). This approach has started to find application also in the study of sectoral innovation systems and processes (Allas, 2014; Allena-Ozolina and Bazbauers, 2017; Aparicio et al., 2016; Bergek et al., 2008; Candido et al., 2017; Grobbelaar, 2005, 2006; Maldonado, 2012; Milling, 2002; Moizer and Towler, 2007; Rodríguez and Navarro Chávez, 2011; Sixt et al., 2018; Suprun, 2018; Suprun et al., 2018, 2019; Uriona et al., 2012; Uriona and Grobbelaar, 2016; Walrave and Raven, 2016; Walz et al., 2016), but a recent review of the literature (Uriona and Grobbelaar, 2019) found that the contribution of the system dynamics approach to research on innovation systems has been limited and that, despite the high value offered by these tools, system dynamics modelling has not yet had the expected scientific impact in this domain.

Similarly, while there is a growing understanding that the application of linear approaches to analyze the complex mechanisms and interactions that occur in the development of the bioeconomy are often insufficient to get a good grasp of the dynamics governing this transition, systems thinking methods have only recently started to be applied in the study of these pathways (Bennich et al., 2018a, 2018b; Blumberga et al., 2018; Stark et al., 2022). Work in this field is just beginning and, as a result, there is a myriad of areas where important research gaps exist. Thus, for example, despite the broad recognition that the bioeconomy is a knowledge-intensive sector that depends largely on public policies and programs, the systems thinking approach has found virtually no application to date in the literature about learning, knowledge, and the role of government in the transition to a circular bio-based economy (see Methodology, below).

Against this backdrop, our study seeks to increase the understanding of how the dynamics of innovation systems influence the development of the circular bioeconomy, exploring how knowledge and learning influence the performance of these processes, and identifying points where interventions could enhance the strengths and overcome the weaknesses to promote growth in this sector of the economy. We focus our analysis on the Andalusian bioeconomy because it is a key component of the region's economy, generating an annual turnover of about 29 billion euros and employing around 300.000 people (approximately 9% of the total) (Institute of Statistics and Cartography of Andalusia, 2022). The significance of this sector led the Regional Government of Andalusia to release a circular bioeconomy strategy in 2018 and become one of the first regions in Spain to acknowledge the opportunities that it offers for sustainable growth and competitiveness (Regional Government of Andalusia, 2018).

To achieve our objective, we address the following questions:

1) What are the underlying causal structures and feedback mechanisms that interact dynamically in Andalusia's bioeconomy system to shape the transition to a circular bio-based economy in the region?
2) What potential learning and knowledge-related points exist in the system where targeted interventions could have significant impact?
3) What priority actions could be implemented at the identified intervention points that would have the highest probability of positive impact?
4) From a systems thinking perspective, what is the role of government in the transition to a circular bio-based economy?

2. METHODOLOGY

We apply qualitative systems modelling methods (Meadows, 2009; Sterman, 2000) to analyze Andalusia's circular bioeconomy and to conduct a qualitative assessment of key learning- and knowledge-related intervention points to develop this sector. System dynamics models are well-suited for the representation of this type of system as they allow us to analyze complex situations, applying a comprehensive view of the whole and at the same time examining the causal relationships among each of its parts. Furthermore, they provide a valuable tool to build theory around behaviours observed within a system and assess the potential impact that management and policy actions could have on it.

In this study we use causal loop diagrams (CLDs) as they are an easy and powerful tool used in system dynamics modelling to provide a visual representation of the elements of a system, their interdependency relationships, and the feedback processes that exist between them. A CLD comprises a set of variables that are connected by arrows that are assigned either a positive (+) or negative (-) sign, according to how a dependent variable is affected when an independent variable changes. The connected variables, in turn, can form positive and negative feedback loops, which are at the heart of system dynamics. These loops are positive or "reinforcing" (R) when a change in a variable circulates along the loop in a way that it reinforces the initial variation, generating growth or acceleration and having a destabilizing effect. And they are negative or "balancing" (B) when a change in a variable circulates along the loop in a way that counteracts the initial variation, acting as a stabilizing force. A feedback loop is deemed to have a reinforcing effect when all the relationships are positive or if it contains an even number of negative links, and it has a balancing effect if it contains an odd number of negative links. Lastly, the existence of lags in the cause-effect relationships between variables is another key aspect of system dynamics and implies that the effects of a change in a variable become evident not immediately, but after some time. A time delay is indicated in a CLD by a perpendicular double line marked in the arrow where it takes place.

Our methodology comprised four steps, as illustrated in Figure 1 and described below.

2.1. Literature review

The first step consisted of a comprehensive review of the literature related to the application of systems thinking to the study of the development of bio-based sectors and the transition to the bioeconomy, with the objective of identifying the factors that influence performance in these processes and detecting research gaps. For this purpose, we applied an approach based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method (Figure 2), using different combinations of the keywords "system dynamics", "systems thinking", "bioeconomy", "bio-based economy", "transition", "innovation", and "innovation system" within article titles, keywords, and abstracts in the Scopus database. After several iterations, the searches that yielded a manageable number of relevant results (under 500) were "bio-based economy" AND "transition" (148 results), "system dynamics" AND "innovation system" (116 results), "bioeconomy" AND "transition" AND "factors" (65 results), "systems thinking" AND "innovation system" (60 results), "bioeconomy transition" (39 results), "system dynamics" AND "bioeconomy" (16 results), "systems thinking" AND "bioeconomy" (9 results), "bioeconomy" AND "transition" AND "variables" (8 results), "transition to the bioeconomy" (8 results), "system dynamics" AND "bioeconomy" AND "transition" (3 results), "transition to the bio-based economy" (2 results), "system dynamics" AND "bio-based economy" (2 results), and "systems thinking" AND "innovation system" AND "CLDs" (1 result). The duplicates were then discarded, a qualitative screening of the remaining articles was performed through a review of the abstracts followed by a full text review, and a total of 30 were retained due to their relevance for our study (Allas, 2014; Allena-Ozolina and Bazbauers, 2017; Barisa et al., 2015; Bautista et al., 2019; Bennich et al.,

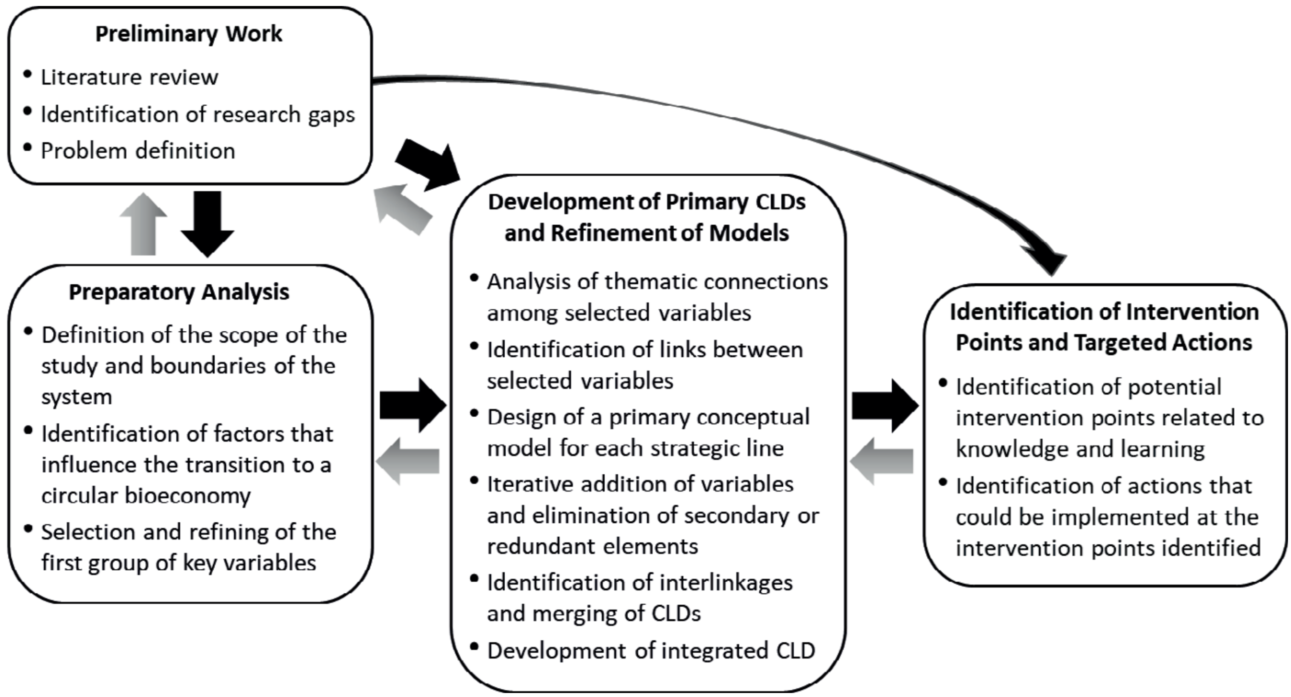

Figure 1. Research methodology flowchart.

2018a, 2018b; Blumberga et al., 2018; Bröring et al., 2020; Candido et al., 2017; Cavicchi, 2020; Chitawo et al., 2018; Galanakis, 2006; Gottinger et al., 2020; Hakim et al., 2016; Jin et al., 2019; Layani et al., 2021; Maldonado, 2012; Milling, 2012; Oriama and Pyka, 2021; Raven and Walrave, 2020; Runge et al., 2017; Samara et al., 2012; Saryazdi and Poursarrajian, 2021; Sixt et al., 2018; Stark et al., 2022; Stern et al., 2015; Suprun, 2018; Suprun *et al.*, 2019; Uriona *et al.*, 2012; Uriona and Grobbelaar, 2019). Furthermore, a search of the Scopus database with the keywords "system dynamics" AND "bioeconomy" AND "knowledge" was conducted and yielded merely two results, of which only one was relevant to our study but was focused on the health sector (Oriama and Pyka, 2021). This finding revealed an important research gap and led us to the decision of focusing the second part of our study on the identification of learning- and knowledge-related leverage points.

Concurrently, a review of the literature on the Andalusian bioeconomy and innovation system was conducted applying the same approach and the keywords "Andalusia", "bioeconomy", "bio-based economy" and "innovation system", to gain a perspective of the regional context. A total of five documents were retained after expanding the quest to Google Scholar and the Google search engine as the Scopus database did not yield any relevant result (Agency for Innovation and Development of Andalusia, 2022; Ministry of Agriculture, Fisheries and Rural Development of Andalusia, n.d.; Regional Government of Andalusia, n.d.; Vázquez and Cohard, 2014; Vázquez, 2017).

2.2. Preparatory analysis

Several definitions of circular bioeconomy were found in the literature due to the vast variety of sectors and activities that make up the bio-based economy sector (Bugge et al., 2016; Giampietro, 2019). Therefore, for the purpose of this study, we decided to focus on the Andalusian Circular Bioeconomy Strategy 2030 (ACBS) (Regional Government of Andalusia, 2018) and thus adopt the scope therein used to define the circular bioeconomy, i.e., the primary and agro-industrial production of food for human consumption are not included. Food products are considered a resource for the circular bioeconomy only if they are deemed unsuitable for human consumption due to non-compliance with regulations or loss of quality during their processing.

The ACBS document comprises four strategic lines and four cross-cutting lines of programmes (Figure 3). It was developed by the Government of Andalusia over the course of nearly two years, in a process coordinated by the Regional Ministry of Agriculture, Fisheries and Rural Development that included bilateral meetings with

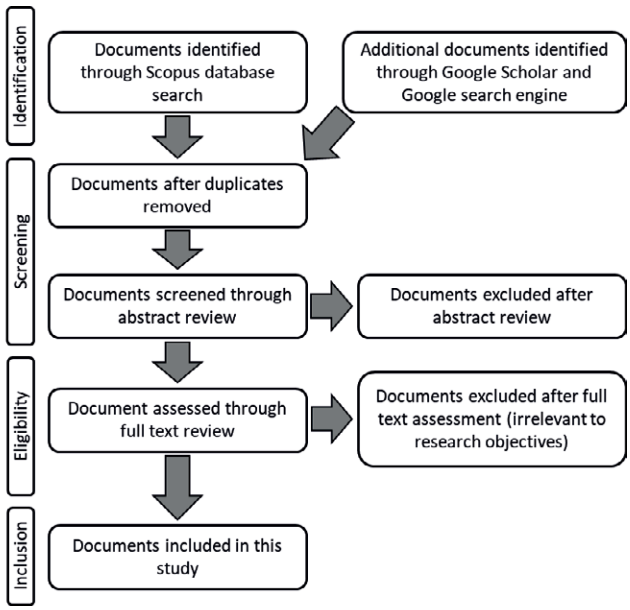

Figure 2. Overview of the document identification, selection and inclusion process followed in this study (Adapted from Page et al., 2021).

various government agencies, the organization of an Andalusian circular bioeconomy forum, and consultations with 53 experts from the private sector, universities, and research organizations. For this reason, it was deemed to contain all the relevant variables and influencing factors required for at least the initial stages of our analysis.

Once the scope was defined, the strategic lines of the ACBS were set as the boundaries of the system for this study and a first group of variables was selected from each one of them, using the 30 articles retained in our literature review as a guiding reference. These were subsequently submitted to further refining based on the Andalusia-related literature and the thematic connections among them was analyzed to further define the boundaries of the system.

2.3. Development of CLDs and refinement of the models

In the next step, the variables selected during the preparatory analysis were used to design a primary conceptual model for each of the four strategic lines, using causal loop diagrams (CLDs) prepared with Vensim PLE software (Ventana Systems, 2022), and links identified in models developed previously for the bio-based sector and other sectoral innovation systems (Allas, 2014; Bennich et al., 2018a, 2018b; Blumberga et al., 2018; Bröring et al., 2020; Candido et al., 2017; Galanakis, 2006; Maldonado, 2012; Milling, 2012; Oriama and Pyka, 2021; Raven and Walrave, 2020; Samara et al., 2012; Saryazdi and Poursarrajian, 2021; Suprun, 2018; Suprun *et al*., 2019; Uriona *et al*., 2012; Uriona and Grobbelaar, 2019).

Subsequently, taking the primary CLDs as the starting point, the models were improved iteratively to portray the relationships among the key variables and factors formulated in the Andalusian strategy, providing a visual understanding of the causal relationships and the feedback loops that shape the reinforcing and balancing forces between the various components of the system. Along this process, several secondary or redundant elements were gradually eliminated to obtain a simple but comprehensive representation of the system with the lowest possible number of elements (Sterman, 2000). The resulting CLDs were subsequently merged into a series of integrated CLDs, to provide an overall view of the system.

2.4. Identification of intervention points and targeted actions

Lastly, the strategic lines and programmes of the ACBS were revisited for a full text analysis of its 17 prescribed measures to identify specific actions related to learning and knowledge that are known for their effectiveness in industrial development and that could be implemented to facilitate the transition to a circular bio-based economy. The actions thus identified were subsequently used to find the appropriate intervention points where their implementation could have meaningful impact (Meadows, 2009).

Throughout the entire process, the literature findings were complemented by the authors' combined experience of over three decades in the analysis, design, and implementation of public policies, strategies and programs for science, technology, innovation, and economic development in both government and the academic sector in North America and the European Union. In addition, preliminary versions of the CLDs and their intervention points were presented for feedback and comments at the ISPIM Innovation Conference 2021 (Berlin, Germany, June 20-23, 2021) and 30 experts at the XIII Agrifood Economics Congress of the Spanish Association of Agri-food Economy (Cartagena, Spain, September 1-3, 2021), which allowed the collection of further contributions that enriched the results.

3. RESULTS

The data gathered from the literature review and analysis of the ACBS led to four conceptual CLDs por-

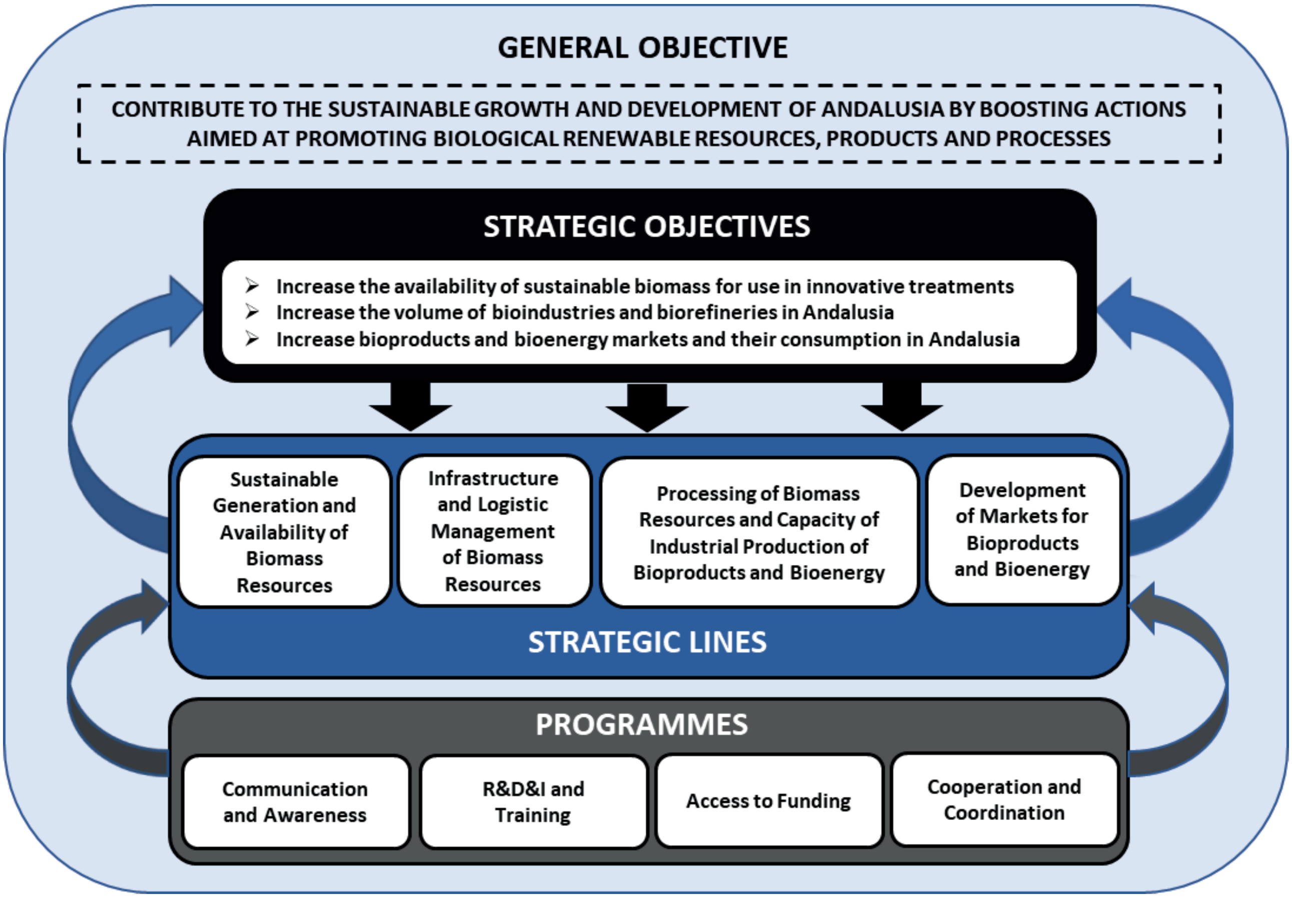

Figure 3. Strategic and instrumental framework of the Andalusian Circular Bioeconomy Strategy 2030 (Adapted from: Regional Government of Andalusia, 2018).

traying the causal relationships among 33 key variables identified from the four strategic lines of the ACBS: (1) sustainable generation and availability of biomass resources, (2) infrastructure and logistics management of biomass resources, (3) processing of biomass resources and capacity of industrial production of bioproducts and bioenergy, and (4) development of markets for bioproducts and bioenergy. Subsequently, after merging them into a series of integrated CLDs, a total of 20 key learning- and knowledge-related interventions points were identified, along with 52 targeted actions that could have meaningful impact on the system.

3.1. Sustainable generation and availability of biomass resources

The first strategic line formulated in the ACBS relates to increasing the availability of biomass resources produced sustainably for their subsequent conversion into bioproducts and bioenergy. During the analysis of the document, several reinforcing feedback loops were identified that would lead to higher "Availability of sustainable biomass resources" (capitalized, Figure 4).

As the main proponent and champion of the regional strategy, government investment in technology and training for sustainable biomass production ("Public investment in technology and training I") drives the development of "Skills in sustainable biomass production" as well as the "Deployment of sustainable technologies for biomass production" both directly (reinforcing feedback loops R1a, R1b, and R1c) and through the enhancement of private investment in these activities (reinforcing feedback loops R2a, R2b, and R2c). All these together trigger an increase in the "Share of land and water used for sustainable biomass production", which in turn leads to a higher "Volume of biomass produced sustainably". The higher "Availability of sustainable biomass resources" thus achieved consequently induces an increase in both the "Use of sustainable biomass in bioindustrial processes" and the "Use of biomass

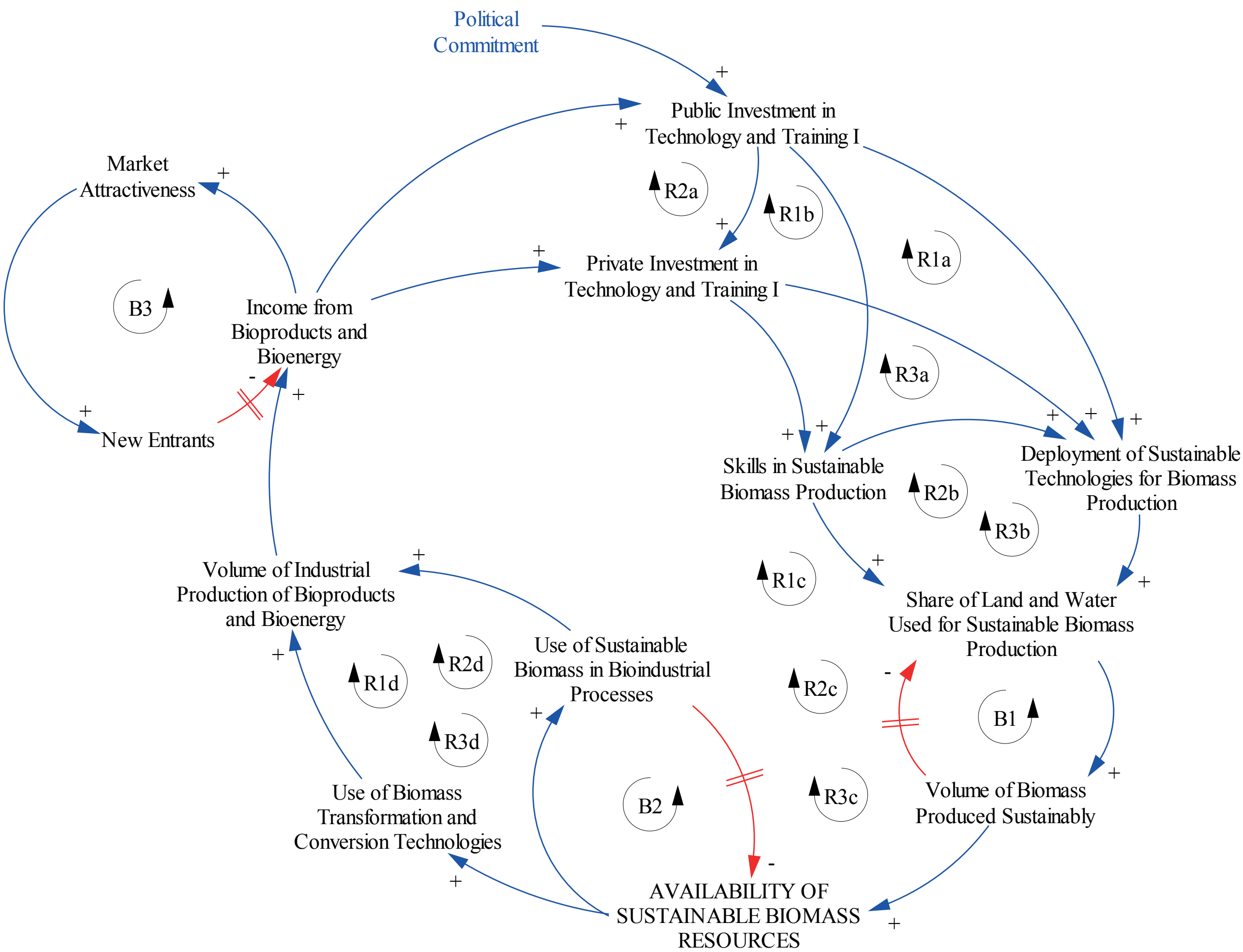

Figure 4. Dynamics suggested to govern the availability of sustainable biomass resources.

transformation and conversion technologies" (reinforcing feedback loops R1d and R2d), resulting in a higher "Volume of industrial production of bioproducts and bioenergy" and increased "Income from bioproducts and bioenergy" (as well as from related services). Lastly, the economic, environmental, and social benefits that accrue from these activities close the loop by prompting more public and private investment in technology and training for sustainable biomass production. The private sector also can promote these cycles (reinforcing feedback loops R3a, R3b, R3c, and R3d), but the impact on the system is lower if it does it alone.

Three balancing feedback loops were identified. Water and land of good quality are often limited resources, but this condition is exacerbated in Andalusia due to the region's geographic characteristics. Therefore, the more resources are used to produce biomass for bioproducts and bioenergy, the lower the potential to further expand sustainable biomass production for these purposes (delayed balancing feedback B1). Likewise, the more biomass is used in bioindustrial processes, the lower the potential to further expand these activities (delayed balancing feedback B2). And as new entrants are attracted to the region's circular bioeconomy industry due to increasing income from bioproducts and bioenergy, higher competition for resources would eventually become a limiting factor (delayed balancing feedback B3).

3.2. Infrastructure and logistic management of biomass resources

The second strategic line described in the ACBS relates to optimizing the management and distribution of biomass resources from the points where they are generated to the bioindustries that use them as inputs. Several reinforcing feedback loops were identified during

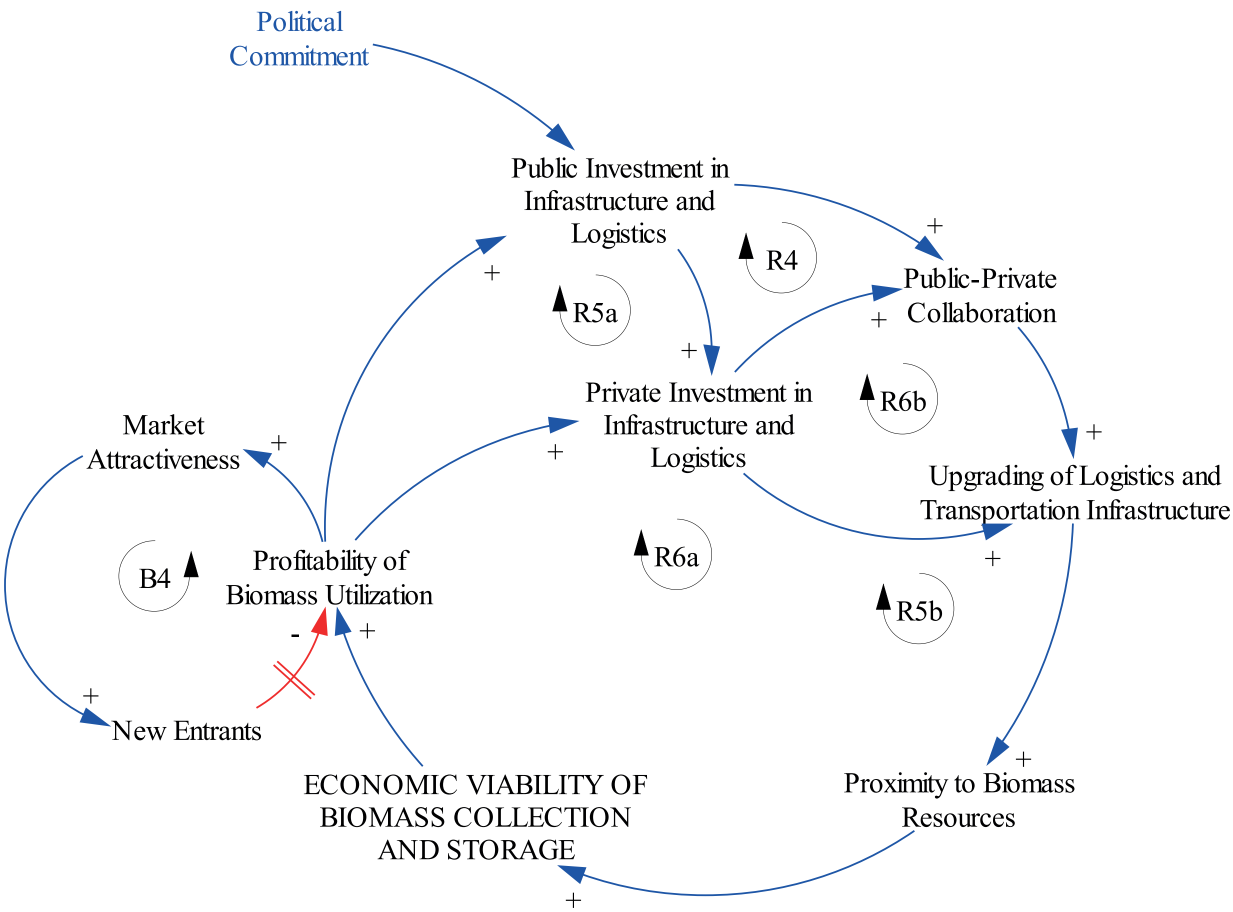

Figure 5. Causal loop diagram displaying the dynamics hypothesized to govern the economic viability of biomass collection, transportation, and storage.

the analysis that would lead to higher "Economic viability of biomass collection and storage" (capitalized, Figure 5).

While private investment alone can have a positive impact on the "Logistics and transportation infrastructure" available to the sector (reinforcing feedback loop R6a), public investment is a key factor for the success of this strategic line of the ACBS through several ways, which include direct contributions to "Public-private collaboration" initiatives (reinforcing feedback loop R4) as well as financial support and market signals that encourage private investment (reinforcing feedback loops R5a, R5b, and R6b).

"Public investment in infrastructure and logistics" plays an important role not only on the construction and maintenance of infrastructure and facilities but is seen as essential to improve knowledge about the volume and location of the biomass resources – through the development of inventories of the biomass available for bioindustrial processes in the region. On the other hand, as agricultural and agro-industrial residues and by-products are typically spread across vast areas (for example, biomass from pruning of olive crops is spread throughout 2.5 million hectares of plantations across the entire region of Andalusia), "Public-private collaboration" is deemed necessary to improve the "Economic viability of biomass collection and storage" by "Upgrading the Logistics and Transportation Infrastructure" and increasing the "Proximity to biomass resources", which in turn would contribute to boost the "Profitability of biomass utilization". Lastly, as the first results of this collaborative work become evident, the model would be replicated across the region through more public and private investment in logistics and transportation infrastructure.

And as in the previous model, the attractiveness of the growing market would attract new entrants which, over time, would have a negative impact on returns because of higher competition for the limited resources available (delayed balancing feedback B4).

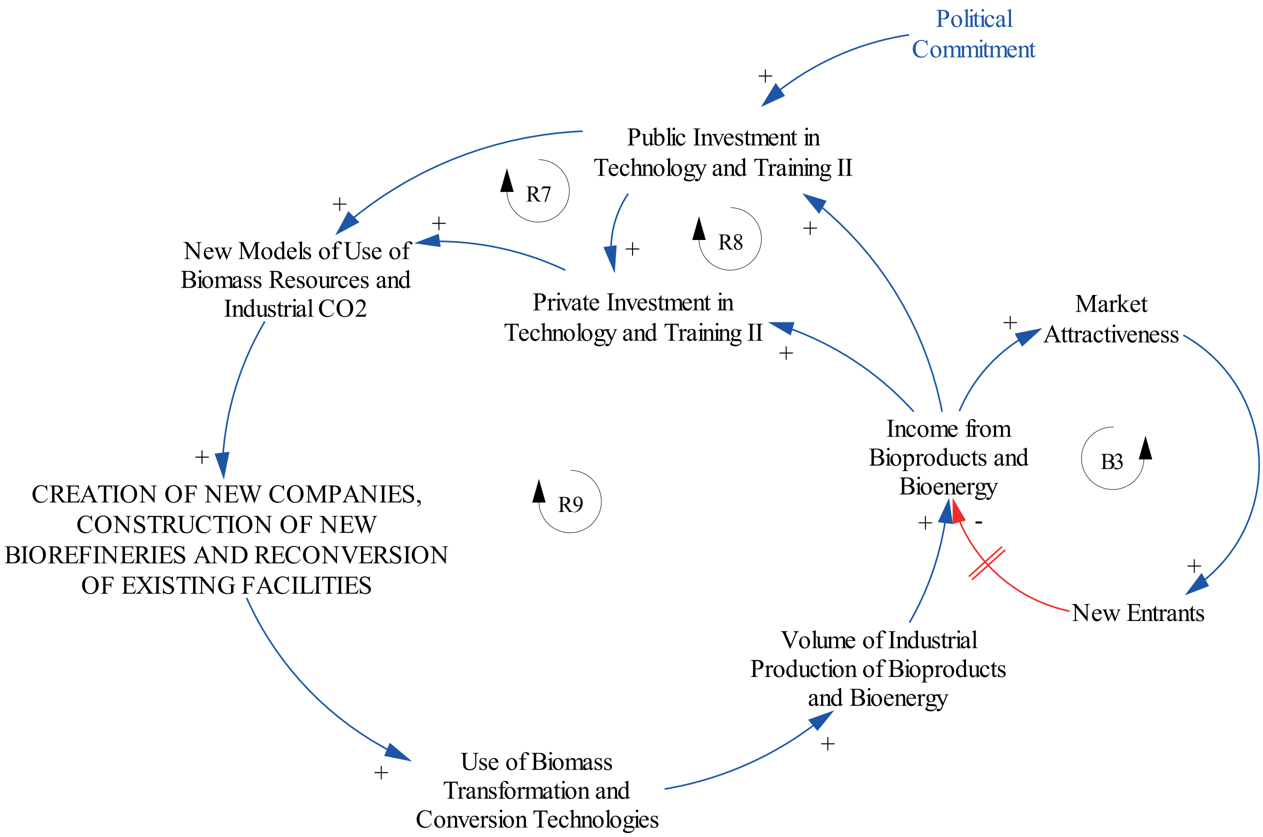

Figure 6. Dynamics suggested to govern the development of industrial capacity to process biomass resources and produce bioproducts and bioenergy.

3.3. Processing of biomass resources and capacity of industrial production of bioproducts and bioenergy

The third strategic line defined in the ACBS comprises actions to support the development of a bio-based industry that optimizes the use of biomass resources in Andalusia, especially through integrated biorefineries. As in the previous cases, several reinforcing feedback loops were identified (Figure 6).

According to this model, investments in technology and training by the public and private sector would lead to the development of "New models of use of biomass resources and industrial CO_2". As synergies are achieved, new companies would be created, new biorefineries would be built, and existing facilities would be reconverted to increase the "Industrial use of transformation and conversion technologies" and expand the "Volume of industrial production of bioproducts and bioenergy". As in the previous models, private investment alone can generate positive results (reinforcing feedback loop R9), but public sector involvement can potentiate the system through direct investments, financial support, and positive market signals (reinforcing feedback loops R7 and R8). The income thus generated from bioproducts and bioenergy (as well as from related services) would produce economic, environmental, and social benefits that would in turn encourage more public and private "Investment in technology and training" for biomass transformation and conversion. However, as in the previous models, once the biomass processing sector reaches a critical mass, its attractiveness would encourage the entry of new players up to a point where the competition for resources would become a limiting factor (delayed balancing feedback B3).

3.4. Development of markets for bioproducts and bioenergy

The fourth and last strategic line formulated in the ACBS consists of actions aimed at consolidating the markets that already exist in Andalusia while promoting and supporting the development of national and international value chains for bioproducts and bioenergy. As described in Figure 7, several reinforcing feedback loops

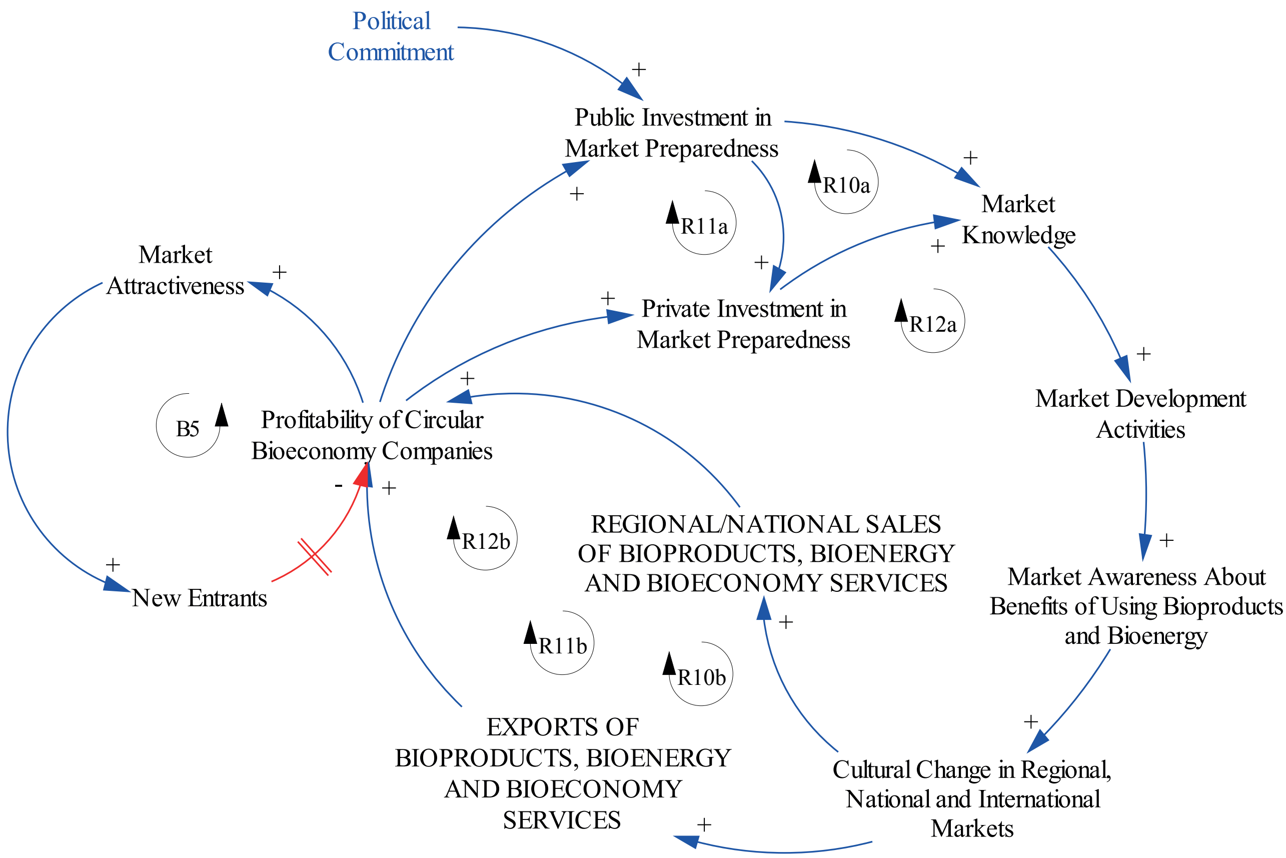

Figure 7. Causal loop diagram displaying the dynamics hypothesized to govern the development of markets for bioproducts and bioenergy.

were identified that would lead to higher sales of bioproducts, bioenergy, and related bioeconomy services.

Once again, synergistic "Investments in market preparedness" by the public and private sector would lead to enhancements in the collective "Market knowledge" about opportunities for bioproducts, bioenergy, and bioeconomy-related services. With this valuable information at hand, both government planning and corporate business plans would be upgraded to support "Market development activities" aimed at increasing "Market awareness about the benefits of using bioproducts and bioenergy" and triggering the "Cultural change in regional, national and international markets" that is needed to switch consumption towards products and energy obtained from sustainable biomass resources. Lastly, higher sales of bioproducts, bioenergy, and related bioeconomy services to local, regional, and national customers (reinforcing feedback loops R10a, R11a, and R12a), as well as in international markets (reinforcing feedback loops R10b, R11b, and R12b) would close the loop by increasing the "Profitability of circular bioeconomy companies", which would in turn stimulate more public and private investments in market development activities. As in the previous strategic lines, the finite availability of biomass resources would eventually become a limiting factor as the attractiveness of the new markets leads to the entry of new market players (delayed balancing feedback B5).

3.5. Combined causal loop diagrams and key intervention points

While the individual CLDs in Figures 4 to 7 depict the dynamics of different dimensions of the system, some interlinkages were identified. Figures 8 and 9 display combined CLDs, highlighting the proposed cross-dimension interlinkages, as well as a total of 20 key learning- and knowledge-related intervention points identified from the ACBS and the literature where targeted actions could have meaningful impact. These were subsequently merged into an integrated CLD (Figure 10) for the ACBS.

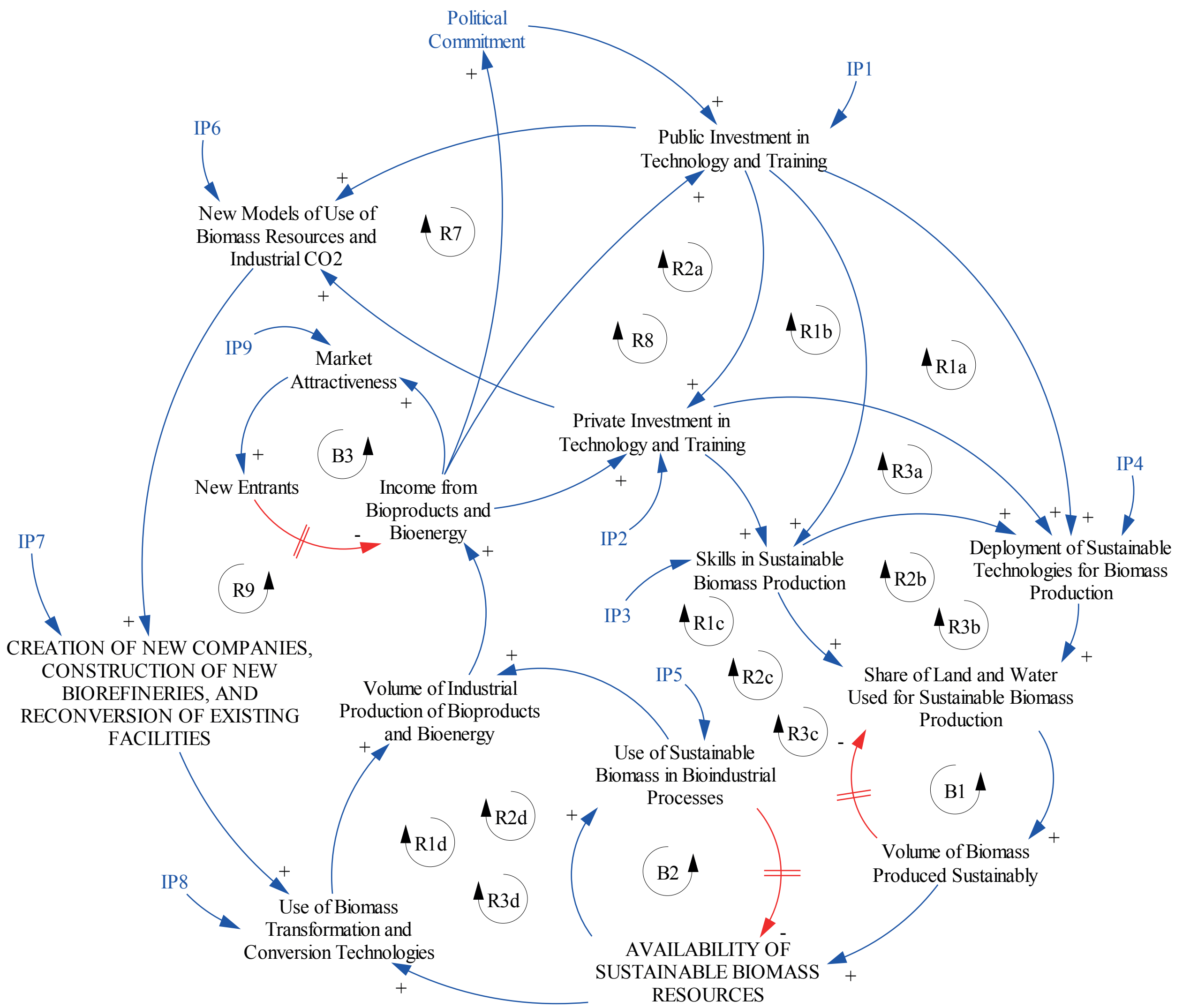

Figure 8. Dynamics suggested to govern the sustainable generation of biomass resources as well as the development of industrial capacity to process biomass resources and obtain bioproducts and bioenergy.

3.5.1. Sustainable generation of biomass resources; development of industrial capacity to process biomass resources and generate bioproducts and bioenergy

An analysis of both the ACBS and Figures 4 to 7 reveals that the strategic lines 1 and 3 of the document have some common variables related to technology and training and, as a result, their respective CLDs merge as shown in Figure 8.

A subsequent evaluation led to the identification of 9 key learning- and knowledge-related points susceptible of intervention. Of these, four (IP1, IP2, IP3, and IP4) are related to public and private investment in technology and training, the development of skills, and the deployment of sustainable technologies, all of which together would lead to an increase of the volume of biomass produced sustainably. Subsequently, activities designed to enhance the sharing of knowledge regarding the use of biomass in bioindustrial processes (IP5) would lead to an increase in the volume of industrial production of bioproducts and bioenergy, which is concurrently potentiated by actions designed to promote learning about new models of use of biomass resources and industrial CO_2 (IP6). Lastly, as new companies are created, new biorefineries are built, and existing facilities are reconverted, the Andalusian circular bioeconomy would benefit significantly from greater access to the growing stock of knowledge about technologies for biomass transformation and conversion, the various types of bioproducts and bioenergy generated from these sources, and the rising income from these activities (IP7, IP8, and IP9). Above all of these, given that the circular bioeconomy is an emerging sector that will require ongoing government support for some time, political commitment to public investments in technology and training is key for its success. Table 1 contains a list of targeted learning- and knowledge-related actions identified from the ACBS and the authors' analysis that could be implemented with meaningful impact at these intervention points.

3.5.2. Economic viability of biomass collection and storage; development of markets for bioproducts and bioenergy

As for the strategic lines 2 and 4 of the ACBS, negligible overlap was observed among them and with the others, as shown in Figure 9.

Of the 11 learning- and knowledge-related intervention points identified for these two strategic lines of the ACBS, four (IP10 to IP13) are related to increasing the economic viability of biomass collection and storage, whereas six (IP14 to IP19) are linked to the commercialization of bioproducts, bioenergy, and bioeconomy services. Interestingly, while a significant part of the activities contained in Figure 8 involve science, technology, and innovation (STI)-based learning processes, actions aimed at building structures and relationships to enhance the doing, using, and interacting (DUI) mode of learning (Jensen et al., 2007; Thomä, 2017) are likely to have higher impact in these strategic lines. Lastly, one intervention point (IP20) was shared by both strategic lines and as noted in the previous figure, political commitment plays a pivotal role due to the emerging nature of the circular bioeconomy sector. Table 2 contains a list of targeted learning- and knowledge-related targeted actions identified from the ACBS and the literature that could be implemented with meaningful impact at these intervention points.

3.6. Integrated causal loop diagram

Figure 10 displays an integrated CLD, highlighting the proposed cross-dimension interlinkages, as well as the central role played by government in the development of this emerging sector of the economy.

4. DISCUSSION

The application of the system dynamics approach to the analysis of Andalusia's circular bioeconomy provides important insights into the complexity of the system due to the existence of non-linear processes, multiple feedback loops, and time delays. Likewise, the models generated in this study provide tools for a better understanding of the potential impact that learning- and knowledge-related interventions by governments and other actors could have on different parts of the development of the circular bioeconomy.

4.1. Learning, knowledge, and innovation

A strong innovation ecosystem based on a balance between science and technology push and market and social pull will play a leading role in the realization of the potential presented by the circular bioeconomy and, in realizing this potential, it will be fundamental to keep in mind that an important aspect of the innovation process is its heterogeneity across sectors, industries, and regions. In this regard, assessing and measuring the underlying processes of learning and knowledge accumulation for innovation has been an ongoing challenge for decades (Abramovitz, 1956; Dosi, 1982; Romer, 1990; Solow, 1957). This has had important repercussions for technology, innovation, and economic development policymaking, which has strongly relied on a linear R&D-based innovation model. Nevertheless, the literature on the topic is increasingly recognizing external knowledge sources as key elements of the innovation process (Doloreux et al., 2020; Fitjar and Rodríguez-Pose, 2013; Isaksen and Nilsson, 2013; Jensen et al., 2007; Santner, 2018) as well as the systemic nature of the innovation systems framework (Uriona and Grobbelaar, 2019).

One of the most valuable efforts to understand how the process of learning and innovating can differ in firms is the work of Jensen et al. (2007), that distinguishes two fundamental forms: the Science, Technology, and Innovation (STI) mode, which focuses on the production and use of codified scientific and technical knowledge; and the Doing, Using, and Interacting (DUI) mode, which focuses on experience-based know-how and informal interactive learning. Since the proposal of this taxonomy, several studies have explored the extent to which these two modes of innovation can be observed in different economic sectors, providing insights into their links with firm innovativeness on the one hand (e.g. Apanasovich et al., 2016; Aslesen and Pettersen, 2017; Doloreux et al., 2020; Figueiredo and Piana, 2021; González-Pernía et al., 2015; Isaksen and Karlsen, 2010; Parrilli and Elola, 2012;

Table 1. Proposed learning- and knowledge-related actions to boost the sustainable generation of biomass resources and enhance the development of industrial capacity to process biomass resources and obtain bioproducts and bioenergy.

Intervention Point	Variable	Proposed Action	Related ACBS Actions
IP1	Public Investment in Technology and Training	· Promote knowledge among public sector staff and policy makers regarding the strengths, needs, gaps, opportunities, barriers, and risks faced by the bioeconomy to improve the quality of public investment decisions in technology and training.	(1.1.1) (1.1.2) (1.2.1) (1.2.2) (2.1.1) (2.1.2) (3.1.1) (3.1.2) (B.1.1) (B.1.3) (B.3.1) (D.1.2) (D.2.1)
		· Foster knowledge among public sector staff and policy makers about alternative ways of collaborative financing as well as about the role that governments can play as early adopters of innovative solutions through instruments such as public procurement of innovation (PPI).	(B.1.2) (C.1.2)
IP2	Private Investment in Technology and Training	· Promote knowledge among the private sector regarding the strengths, needs, gaps, opportunities, barriers, and risks faced by the bioeconomy to improve the quality of private investment decisions in technology and training.	(1.1.1) (1.1.2) (1.2.1) (1.2.2) (2.1.1) (2.1.2) (3.1.1) (3.1.2) (B.1.1) (B.1.3) (B.3.1) (D.1.2) (D.2.1)
		· Promote knowledge among the private sector about financial instruments available for the circular bioeconomy.	(C.1.1) (C.1.2)
		· Upgrade management skills in the private sector to increase the absorptive capacity of companies to receive public funding and improve the quality of their investment decisions in technology and training.	(1.2.1) (3.1.2) (3.2.1) (B.3.1)
		· Foster initiatives to disseminate knowledge among local, national, and foreign investors about the region's competitive advantage in the bioeconomy and specific investment opportunities in R&D, technology, and training.	(1.1.1) (2.1.1) (3.2.1) (3.2.2) (C.2.1) (C.2.2)
IP3	Skills in Sustainable Biomass Production	· Implement mechanisms and tools to increase the interaction between all levels of the education system and the actors involved in the generation of biomass to promote technical advice, education and training in matters related to sustainable practices. Adjust the offer to the needs of the market.	(1.2.1) (1.2.2) (B.1.2) (B.1.4) (B.1.5) (B.2.1) (B.3.1) (B.3.2)
		· Develop guidelines and case studies to disseminate knowledge about practices that have shown good results for the sustainability of the generation of biomass resources.	(1.2.1) (1.2.2) (B.1.3) (B.1.4)
IP4	Deployment of Sustainable Technologies for Biomass Production	· Implement mechanisms and tools to increase the interaction between all levels of the education system and the actors involved in the generation of biomass to promote technical advice, education and training in matters related to sustainable technologies. Adjust the offer to the needs of the market.	(1.2.1) (1.2.2) (B.1.2) (B.1.4) (B.1.5) (B.2.1) (B.3.1) (B.3.2)
		· Prepare technology surveillance reports to disseminate knowledge about current and upcoming technologies available for sustainable biomass production.	(1.2.1) (1.2.2) (B.1.3) (B.1.4)
		· Develop guidelines and case studies to disseminate knowledge about technology solutions that have shown good results for the sustainability of the generation of biomass resources.	(1.2.1) (1.2.2) (B.1.3) (B.1.4)
IP5	Use of Sustainable Biomass in Bioindustrial Processes	· Develop and regularly update an inventory of biomass resources in the region to disseminate knowledge about the types and volumes available, their physical and chemical characteristics, their geographic location, and the distribution of their availability over time (seasonality).	(1.1.1)
		· Develop and regularly update a georeferenced inventory of potential users of biomass resources.	(2.1.1)

Intervention Point	Variable	Proposed Action	Related ACBS Actions
IP6	New Models of Use of Biomass Resources and Industrial CO_2	· Foster the incorporation of technical and business skills into the knowledge of people who work in bioindustries to improve the sustainability of companies and increase the addition of value to the region's biomass resources.	(3.1.1) (3.1.2) (B.1.2) (B.1.3) (B.1.4) (B.1.5)
		· Promote collaboration and the generation of synergies within the bioeconomy sector and with other industries to advance new models of use of biomass resource flows and industrial sources of CO_2.	(3.1.3) (B.1.4) (B.1.5) (B.2.1) (B.2.2)
		· Establish and support business clusters, incubators, accelerators, and mentoring programs to promote technology and knowledge transfer among the different innovation system actors interested in the bioeconomy.	(B.1.2) (B.1.5) (D.1.1)
		· Develop guidelines and case studies based on regional, national, and international success stories to disseminate knowledge about new models of use of biomass resources and industrial CO_2.	(3.1.2) (B.1.3) (B.1.4)
IP7	Creation of New Companies, Construction of New Biorefineries, and Reconversion of Existing Facilities	· Leverage the knowledge and experience acquired in sectors such as the biodiesel industry to promote the development of higher value-adding activities and the conversion of existing facilities to biorefineries.	(3.2.2)
		· Develop guidelines and case studies based on regional, national, and international success stories to disseminate knowledge about the planning and implementation of bioindustries and biorefineries.	(3.1.2) (B.1.3) (B.1.4)
IP8	Use of Biomass Transformation and Conversion Technologies	· Implement mechanisms and tools to increase the interaction between all levels of the education system and the bio-based industry to promote technical advice, education and training in matters related to the use of technologies for sustainable biomass transformation and conversion. Adjust the offer to the needs of the market.	(3.1.1) (3.1.2) (B.1.2) (B.1.4) (B.1.5) (B.2.1) (B.3.1) (B.3.2)
		· Foster collaboration and the establishment of regional, national, and international alliances and multi-actor platforms to facilitate the transfer of knowledge and the adoption of sustainable technologies generated by the R&D and innovation system.	(3.1.3) (B.1.4) (B.1.5) (B.2.1) (B.2.2) (D.1.1)
		· Promote the establishment of technology sandboxes and pilot plants for process development and scale-up of sustainable bio-based products and processes.	(B.1.2) (Authors' analysis)
		· Prepare technology surveillance reports to disseminate knowledge about current and upcoming technologies for sustainable biomass transformation and conversion.	(3.1.1) (B.1.3) (B.1.4)
		· Develop guidelines and case studies to disseminate knowledge about technology solutions that have shown good results for the sustainable transformation and conversion of biomass.	(3.1.1) (3.1.2) (B.1.3) (B.1.4)
IP9	Market Attractiveness	· Develop a portfolio of successful projects, technological innovations, business initiatives, and business models, for each of the links in the value chains associated with the bioeconomy to expand knowledge about the opportunities presented by the bio-based economy across various stakeholder groups.	(3.1.1) (3.1.2) (B.1.3) (B.1.4)

Santner, 2018; Thomä, 2017) and with the geography of innovation on the other (Fitjar and Rodríguez-Pose, 2013; Parrilli and Alcalde-Heras, 2016).

Overall, the learning- and knowledge-related actions identified in this study to accelerate Andalusia's transition from a linear bio-based economy to a sustainable circular bioeconomy support the view that an innovation system that encourages a combination of STI and DUI activities will have the greatest potential of success as each company will choose the learning mode that best suits its scientific, technological, and geographic context (Fitjar and Rodriguez-Pose, 2013; Parrilli and Alcalde-Heras, 2016). Thus, when confronted with the current scenario, the cause-effect relationships and causal cycles herein described suggest that the Andalusian innovation system needs greater collaboration and coordination along and across the triple helix to support the development, commercialization, and diffusion of

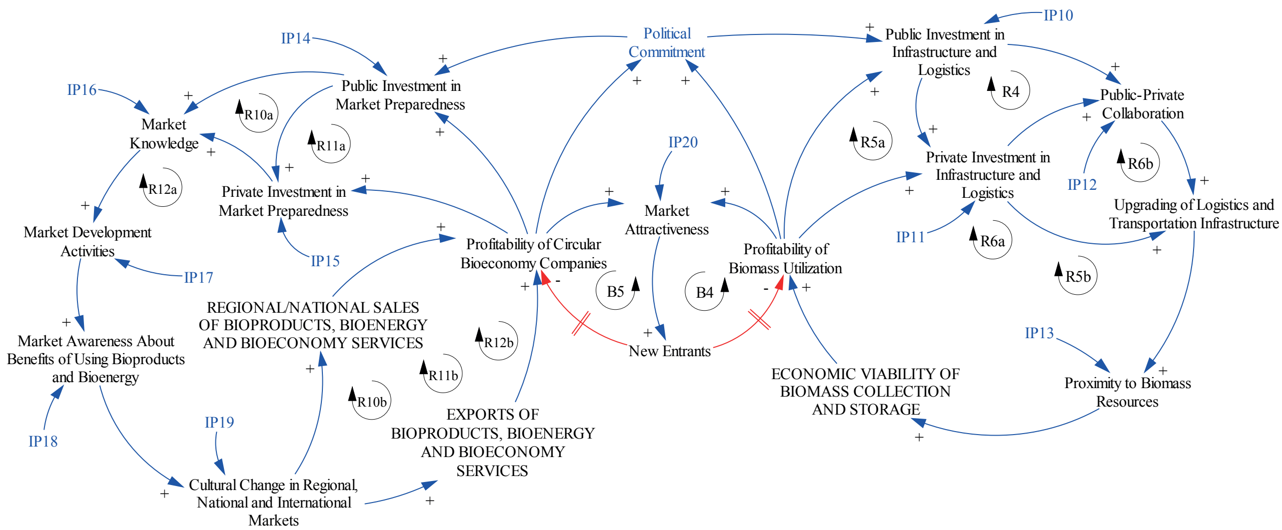

Figure 9. Causal loop diagram displaying the dynamics hypothesized to govern the economic viability of biomass collection and storage as well as development of markets for bioproducts and bioenergy.

innovative solutions, all of which are necessary for the development of critical mass in the region's circular bioeconomy.

4.2. *The role of government*

One of the main challenges faced by transition regions such as Andalusia in their attempt to close the gap with developed regions is to find the right balance between technological innovation and technological imitation as well as the choice of technologies to be developed and imitated (Atkinson and Stiglitz, 1969; Basu and Weil, 1998; Lin, 2003).

For less developed and transition regions, fulfilling the promise of faster economic growth through technological imitation is not an easy task. Studies on technology diffusion have shown that the process of closing the technology gap requires a significant amount of effort and institution building, and that in this process less developed and transition regions generally face larger requirements for capital and other advanced factors than developed regions. Thus, in addition to the licensing fees, regions that adopt technologies from leading regions need to incur expenses in the retraining of human capital, organizational restructuring, and so on (Stoneman, 1983). Furthermore, as the characteristics of new technologies are strongly influenced by the business environments in which they are developed, large differences between regions can represent serious barriers for their transfer. Among the factors that have been suggested to play a crucial role in a region's ability to import technology are its political, commercial, industrial, and financial institutions, as well as national characteristics such as market size and the relative supply of factors of production (Abramovitz, 1986; Caselli and Coleman, 2001; Chen and Wang, 2021; Keller, 2004). Technological change is therefore the combined result of innovation and learning activities within domestic organizations, and of the interaction among them and with their environment. It thus becomes obvious that firms, with their different combinations of intrinsic competencies and business strategies, are key players in this process (Fagerberg, 1994).

As the costs of adoption of new technologies tend to exceed the benefits obtained, these are often not adopted as soon as they become public (Stoneman, 1983). The process of technological diffusion then occurs gradually, with a few firms adopting the technology first and the others following in a process that can take more than a decade or even stop before its completion (Detragiache, 1998). Remarkably, as the followers have the possibility of copying the adaptive efforts of the pioneers and, at the same time, have access to more skilled labor trained by the early adopters, the costs of adoption tend to decrease as more firms import the technology. Based on the premise that early adopters create positive externalities for the followers, Detragiache (1998) proposed that, once technology adoption starts, less developed regions tend to converge to the level of developed regions as more firms adopt the new technology. Accordingly, different degrees of economic convergence among regions are explained by differences in the rate of diffusion of

Table 2. Proposed learning- and knowledge-related actions to potentiate the economic viability of biomass collection and storage and the development of markets for bioproducts and bioenergy.

Intervention Point	Variable	Proposed Actions	Related ACBS Actions
IP10	Public Investment in Infrastructure and Logistics	· Improve knowledge about biomass resources and industrial sources of CO_2 among public sector staff and policy makers in terms of those factors that determine their logistics, as well as about the infrastructure that is required to ensure the supply of biomass to operators, users, and bioindustries.	(1.1.1) (1.1.2) (2.1.1) (2.1.2) (2.2.1) (2.2.2) (B.1.3) (B.3.1) (D.1.2) (D.2.1)
		· Promote knowledge among public sector staff and policy makers about potential users of biomass resources and infrastructure gaps in the region.	(2.1.1)
		· Foster knowledge among public sector staff and policy makers about alternative ways of collaborative financing and public-private partnerships (PPP).	(C.1.2)
IP11	Private Investment in Infrastructure and Logistics	· Upgrade technical and management skills in the private sector to increase the absorptive capacity of companies to receive public funding and improve the quality of their investment decisions in infrastructure and logistics for biomass collection, transportation, pretreatment, and storage.	(2.1.2) (3.1.2) (B.3.1)
		· Promote knowledge among the private sector about financial instruments available for the circular bioeconomy.	(C.1.1) (C.1.2)
		· Promote knowledge within the private sector about alternative ways of collaborative financing and public-private partnerships (PPP).	(C.1.2)
		· Foster initiatives to disseminate knowledge among local, national, and foreign investors about the region's competitive advantage in the bioeconomy and specific investment opportunities in infrastructure and logistics for biomass collection, transportation, pretreatment, and storage.	(1.1.1) (2.1.1) (2.2.1) (C.2.1) (C.2.2)
IP12	Public-Private Collaboration	· Develop and regularly update an inventory of biomass resources in the region to improve public and private sector knowledge about the types and volumes available, their physical and chemical characteristics, their geographic location, and the distribution of their availability over time (seasonality).	(1.1.1)
		· Improve public and private sector knowledge about both the infrastructure needed and available for the collection, transportation, pretreatment, and storage of the different types of biomass resources.	(2.1.2)
		· Develop and regularly update a georeferenced inventory of potential users of biomass resources.	(2.1.1)
		· Develop guidelines and case studies to improve public and private sector knowledge regarding best practices in public-private collaboration and about current and upcoming solutions for collection, storage, pretreatment, and transportation of biomass resources.	(2.1.2) (B.1.3) (B.1.4)
IP13	Proximity to Biomass Resources	· Promote the transfer of knowledge and the adoption of technologies associated with bioenergy, bioindustries, and small-scale biorefineries established around new local value chains.	(1.1.1) (3.1.1) (3.1.2) (3.1.3) (3.2.1) (3.2.2) (B.1.4) (B.1.5)
IP14	Public Investment in Market Preparedness	· Improve knowledge among public sector staff and policy makers regarding the needs and gaps faced by the bio-based sector in matters related to market preparedness.	(B.3.1) (B.3.2)
IP15	Private Investment in Market Preparedness	· Promote knowledge among the private sector about financial instruments available for the circular bioeconomy.	(C.1.1) (C.1.2)
		· Upgrade management skills in the private sector to increase the absorptive capacity of companies to receive public funding and improve the quality of their investment decisions in market preparedness.	(B.3.1) (B.3.2)

Intervention Point	Variable	Proposed Actions	Related ACBS Actions
IP16	Market Knowledge	· Carry out and disseminate market studies and feasibility analyses to determine supply and demand, prices, and distribution channels for bioproducts, bioenergy and services linked to the circular bioeconomy.	(4.1.1)
		· Prepare, regularly update, and disseminate prospective studies on consumption trends and new uses of bioproducts and bioenergy, as well as analyses of areas and/or sectors where there is potential for the introduction of bio-based products in their value chains.	(4.1.2)
		· Foster interaction and knowledge exchange among bio-based companies and with actors of other industry sectors. Facilitate communication and cooperation among the different agents, especially with the nonrenewable sector, to promote the identification of potential synergies.	(3.1.3) (4.1.2) (B.1.5) (B.2.1) (B.2.2)
IP17	Market Development Activities	· Foster knowledge exchange among bio-based companies and with actors of other industry sectors to identify potential synergies and promote cooperation.	(B.1.5) (B.2.1) (B.2.2)
		· Promote knowledge among public sector staff and policy makers about the role that governments can play as early adopters of innovative solutions through instruments such as public procurement of innovation (PPI).	(B.1.2) (C.1.2)
		· Upgrade international business skills in the private sector to increase the quality of lead generation and conversion in foreign markets.	(B.3.1) (B.3.2) (Authors' analysis)
		· Monitor the evolution of the different links that make up the value chains of bioproducts and bioenergy (supply of raw materials, production, and commercialization) and promote knowledge exchange across the bio-based sector to improve efficiencies and ensure its ability to meet market demand in the medium and long term.	(3.1.3) (B.1.5) (B.2.1) (B.2.2) (D.1.1) (D.1.2) (D.3.2)
IP18	Market Awareness About Benefits of Using Bioproducts and Bioenergy	· Foster knowledge exchange between the bio-based industry and actors of other sectors of the economy and civil society (such as consumer associations) to promote the differentiating features and added value of bioproducts and bioenergy as well as the positive externalities of the bioeconomy.	(4.2.1) (4.2.2) (A.1.1) (A.1.2)
		· Promote the creation of certification and traceability protocols for bioproducts and bioenergy as tools for knowledge transfer across the bioeconomy and to actors of other economic sectors and civil society.	(4.2.1) (A.1.2)
IP19	Cultural Change in Regional, National and International Markets	· Improve knowledge and business training of public service staff and policy makers in matters related to the bioeconomy, its positive externalities, and the use of assessment tools and instruments such as life cycle analysis and the measurement of the carbon and water footprint of entire value chains.	(4.2.2) (A.1.1) (A.1.2) (B.3.1)
		· Improve knowledge and skills of bio-based companies in matters of full cycle sustainability and the efficient use of all the resources destined for the manufacture of their bioproducts or bioenergy, or for the services that they provide. Promote the use of assessment tools and instruments such as life cycle analysis and the measurement of the carbon and water footprint of their entire value chains.	(4.2.2) (B.3.1)
		· Upgrade the absorptive capacity of the regional economy and society through the introduction of the bioeconomy in the contents of compulsory primary and secondary education, post-compulsory (high school and intermediate vocational training) and higher education (university, continuing education, and advanced vocational training).	(B.3.1) (B.3.2)
		· Implement behavioral science (nudging) tools to promote learning and improve decisions about the sustainable use of bio-based products and energy.	(Authors' analysis)
IP20	Market Attractiveness	· Develop a portfolio of successful projects, initiatives, and business models to expand knowledge about the benefits of investing in infrastructure for collection, transportation, pretreatment, and storage of biomass resources.	(B.1.3)
		· Develop and disseminate a portfolio of guidelines and case studies about successful initiatives and business models for the introduction of bioproducts, bioenergy, and bioeconomy-related services in regional, national, and international markets.	(B.1.3)

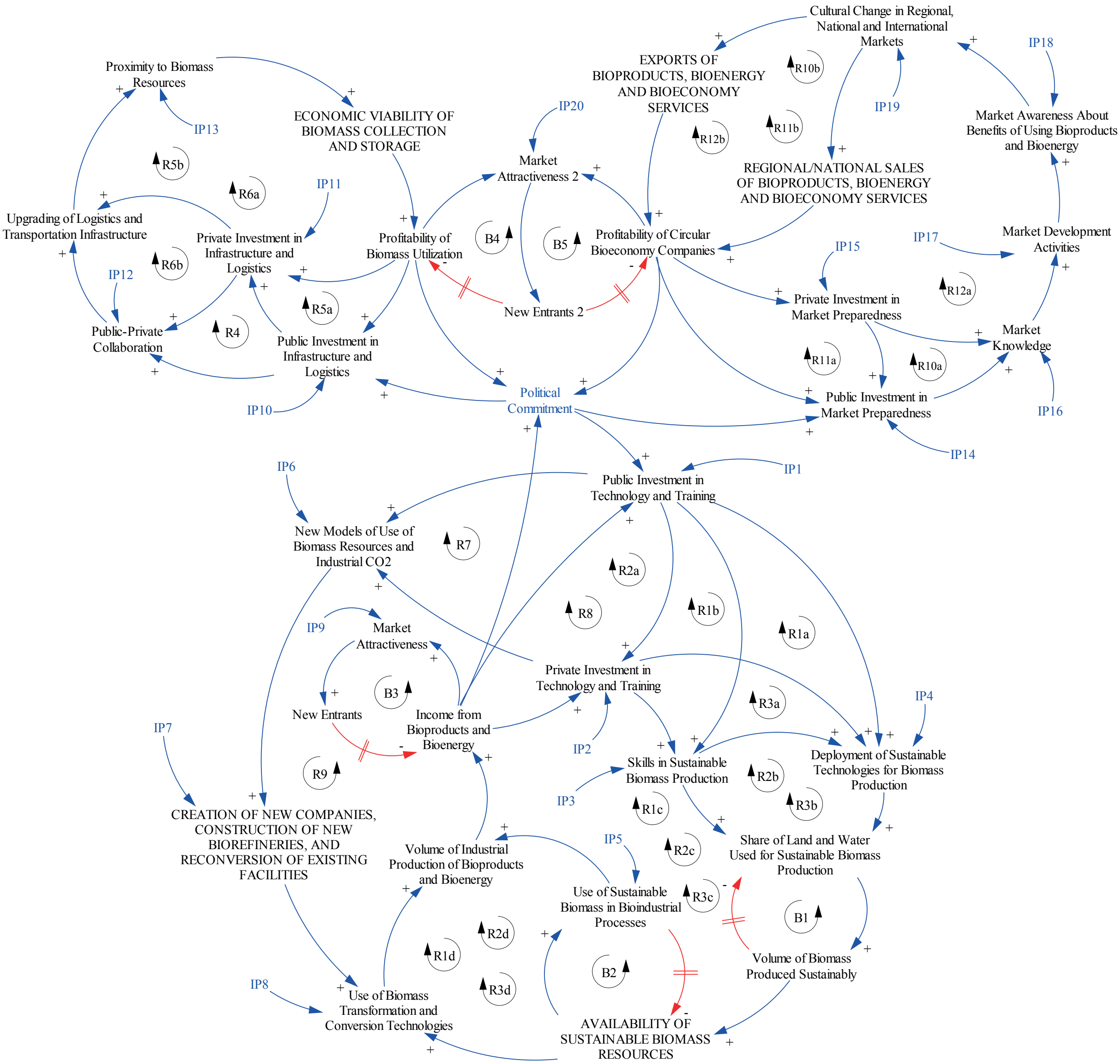

Figure 10. Integrated causal loop diagram displaying the main cause-effect relationships and causal cycles involved in the four strategic lines comprised in the Andalusian Circular Bioeconomy Strategy.

the imported technologies, whereas convergence failure occurs when the adoption costs are too high or when technology diffusion stops before it is completed. Furthermore, this model can successfully account for the fact that economies of transition regions are generally dualistic, i.e., small, traditional firms normally operate along with modern enterprises. In this scenario, it has been argued that when a technology is transferred from a developed region to less developed regions, the discrepancies between the labor skills lead to marked differences in factor productivity and output per capita and, for this reason, governments of less developed and transition regions need to increase their investments in human capital formation (Acemoglu and Zilibotti, 2001).

In this regard, our findings show that the role of government in supporting learning and knowledge-related processes is key for the development of the circular bioeconomy, which can be explained by the pervasiveness of information asymmetries in the sector, its intensity in knowledge and innovation, and its position in the confluence of several technological areas. This is supported by a recent causal mapping analysis of political structures in bioeconomic transitions based on the case of renewable energy political lobbying in six countries (Palmer et al., 2022), and is in agreement with the New Structural Economics framework postulated by Lin (2003, 2010), whereby the positive impact of government in this kind of scenario is higher when it seeks to help companies to overcome information and coordination costs about new industries, markets, and technologies; coordinate investment between companies and industries; and internalize the externalities linked to information by compensating pioneering companies through tools such as guarantees and fiscal incentives. Furthermore, from the innovation policy perspective, a combination of supply-driven policies aimed at the commercialization of research results will be required to foster the STI mode of learning, along with demand-driven policies aimed at supporting the DUI mode of learning for the development of products or services to specific markets (Isaksen and Nilsson, 2013). Lastly, due to the emerging nature of the concept, the circular bioeconomy sector is likely to require ongoing government support for some time, and for this reason political commitment to public investments in technology and training will be key to its success. In Andalusia, both the ACBS and the bill for the Circular Economy Law of Andalusia (LECA) that has recently been sent by the Government Council to the regional Parliament for deliberation are the two most important initiatives currently underway in this direction.

5. CONCLUSIONS AND FUTURE RESEARCH

The results outlined in this paper provide an initial understanding of the dynamics of Andalusia's bioeconomy and the identification of intervention points where targeted actions could be undertaken to accelerate the transition from a linear bio-based economy to a sustainable circular bioeconomy. The models generated in this study provide tools for a better understanding of the potential impact that interventions by governments and other actors could have on the development of the circular bioeconomy. Overall, when confronted with the current scenario, the preliminary cause-effect relationships and causal cycles herein described suggest that the Andalusian innovation system needs greater collaboration and coordination along and across the triple helix to support the development, commercialization, and diffusion of innovative solutions, all of which are necessary for the development of critical mass in this emerging sector of the economy. While the CLDs herein described provide structural insight into the system, an avenue for future research involves the development of quantitative models using stock and flow diagrams to evaluate the sensitivity of the intervention points, using historical data as a reference.

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