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Modelling the Transition to a Circular Agriculture - A Systems Dynamics Perspective

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ABSTRACT

Designing efficient and sustainable pathways for ensuring the transition to a circular economy is one of the main challenges to which an answer must be found, regardless of the economic sector, activity field or geographic area of interest. In order to improve the planet natural resource conservation systems, the main representative institutions and policy makers have implemented a series of strategies and directives, all over the world. From a simple crossing through relevant documents, assumed at global level such as: The 2030 Agenda for Sustainable Development, United Nations 2015, regional level: The New Circular Economy Action Plan, EC 2020 or national level: Recovery and Resilience Plan of Romania, 2023, the main common denominator it can be identified - focusing on finding the optimal balance between the environmental resources rational exploitation, protection and developing competitive economy systems. The bioeconomy involves the use of renewable biomass, including raw material obtained from different categories of secondary products, for the production of finished products in the economy. Interest in the bioeconomy has grown over the last decade, and this study analyses the potential of biomass and circular bioeconomy models in the agricultural sector, using systemic modelling approaches. In this sense, studies and models of bioeconomy and circular economy applied at the regional and European level are presented, specifically for dynamic system modelling methods. Finally, we propose studying a circular bioeconomy pilot model for sunflower production in Romania, highlighting the potential of biomass and secondary products from this crop. The use of sunflower by-products in various applications, such as animal feed, biofuels, functional food ingredients or bio-composite materials, underlines their importance in promoting circular economy practices.

Keywords: circular economy, causal loop diagrams, system dynamics, sustainable production, sunflower.

INTRODUCTION

The concepts of bioeconomy and circular economy are becoming more and more relevant in the context of the challenges faced by contemporary society, such as the climate change adaptation and mitigation, environmental conservation and protection as well as efficient management of natural resources. The core of the bioeconomy concept is the utilisation of renewable biomass obtained from different categories of by-products. According to EC, a definition for by-products term is "an incidental product deriving from a manufacturing process or chemical reaction, and not the primary product or service being produced" (EC, Glossary item, 2024). Depending on typology, by-products can be reusable and introduced to a new market, thus generating new incomes for the producers, which has also positive impact on economy, at the macroeconomic level.

In the last decade, the interest for circular bioeconomy concept and its main principles increased in the international scientific publications, but also regarding the financed research directions and project outcomes, not only at the European level but also worldwide (Conțescu et al., 2023; Rodino et. al. 2023). Although the concept of circular economy is a significant part of bioeconomy concept, in practice is quite difficult closing the loop completely, at the level of economic process (Lazăr C. et al., 2022).

In the context of increasing pressure on natural resources, circular agriculture has become a key concept included in efforts to promote sustainable development and address the challenges of food security, climate change and ecosystem degradation.

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Circular farming is aiming to minimize the inputs while maximizing the closure of productive cycles, especially those involving fertilisers, carbon, energy and water. It is to take into account, however, that the optimal design of these cycles is varying as a function of various specific factors such as soil quality, crop type and climate conditions. As a result, there is no universally applicable model for circular agriculture. Generally, it is considered that circular farmers may experience slightly lower incomes in the short term, but they will have a clearer path toward long-term profitability and sustainable farm management. In this sense, dynamic modelling of agricultural circular systems represents a promising approach for understanding the complexity of these systems and for identifying effective pathways to implement circular economy principles.

In this paper, we propose the exploration of how dynamic systems modelling could contribute to the understanding and implementation of practical processes associated with circular agriculture in the context of the bioeconomy. In the investigation process, we seek to find answers to questions related to the optimization of agricultural production in a circular framework. The main goal was to develop a methodology to establish a balance between implementing principles of circular economy in the agriculture sector and ensuring the feasibility characteristic in relation with the economic perspective.

MATERIAL AND METHODS

The study involves a brief presentation of important concepts such as the bioeconomy and circular economy, as well as legislative framework, at global, European and regional level. In fulfilling the main objective of this study, the biomass potential observed and presented in the representative literature overview taking into consideration the field crop production is also analysed.

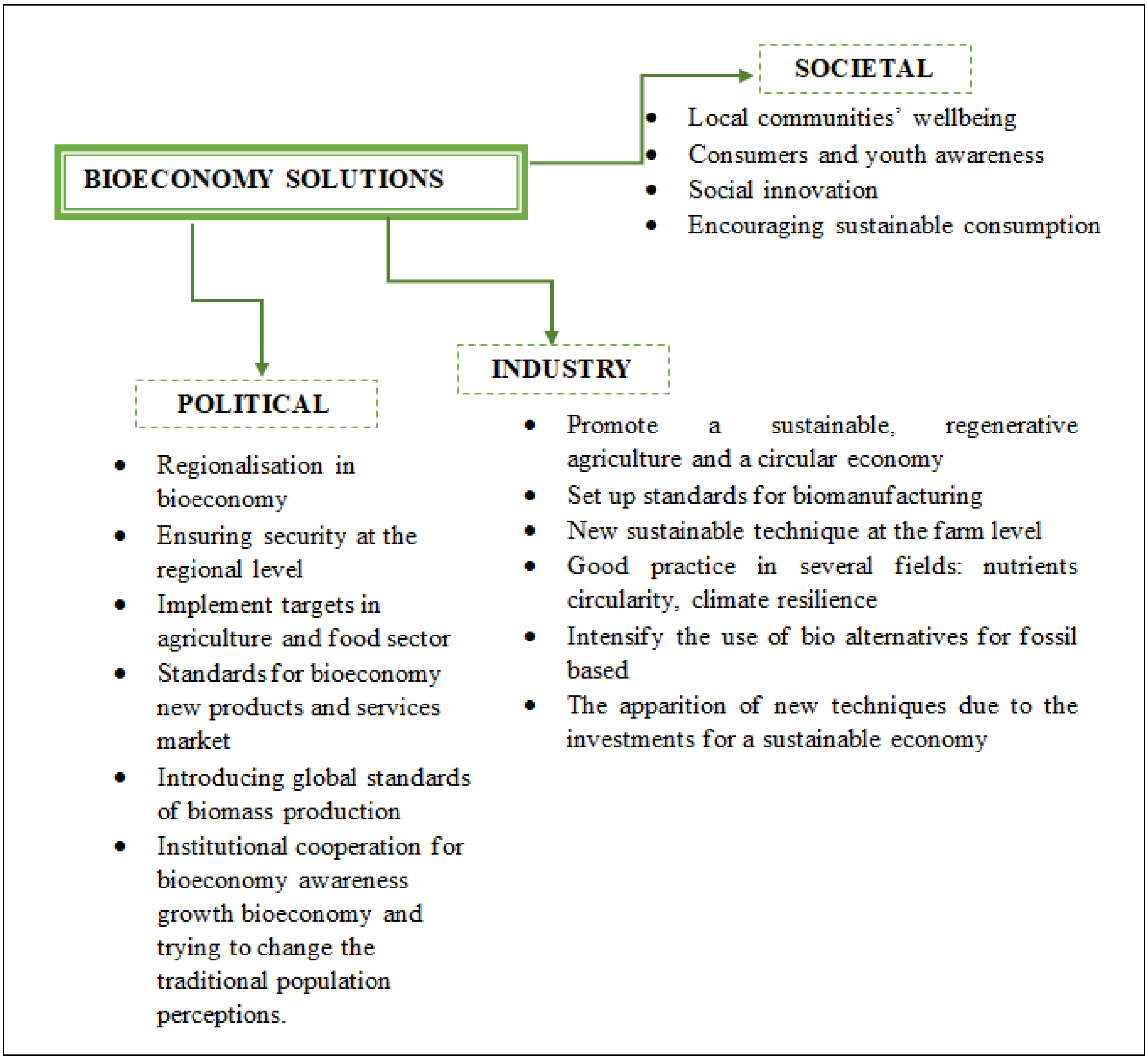
Therefore, in the process of finding efficient transition pathways to circular bioeconomy, the research questions were: Which are the main factors that influence transition to circular bioeconomy at farm level? Can be these factors quantified or their level represents an uncertainty? At the farm level, which are the alternatives for the exploitation of by-products for a specific crop resulted from agriculture process? A system dynamic (SD) approach was applied, invented in 1958 by Jay W Forrester (Dangerfield, 2014). Also, Causal Loop Diagrams (CLDs), a component of SD is used in order to present the main identified interactions between main variables of research. Finally, we propose to outline a dynamic modelling methodology adapted to the specifics of circular agriculture, with an emphasis on identifying and quantifying the main variables and interdependencies that influence the agricultural system.

RESULT AND DISCUSSIONS

Bioeconomy and circular economy - conceptual signification and main legislative framework

At European level, the bioeconomy strategy aims to promote a transition to a sustainable and renewable economic system based on the rational use of biological resources and technological innovations (EC, 2018, Bioeconomy strategy). Regarding the circular bioeconomy framework several strategic documents may be mentioned, component of The European Grean Deal (EC, 2020): EU biodiversity strategy for 2030 Farm to Fork Strategy, Zero pollution action plan (EC, 2020). Each of the strategies has specific targets but also it can be observed the common ambition, to change the conventional approach according to which the economic growth and development is related to the conventional resource use.

The European Circular Economy Plan is an ambitious plan to transform the way society produces, consumes and manages available resources. This strategy is targeted at reducing dependence on finite resources, minimize the production of waste and promote innovative industrial processes towards closing productive cycles. This EU plan objective is to stimulate sustainable economic growth by promoting an economy that is no longer based exclusively on the exploitation of natural resources, but that uses and recycles existing materials in an efficient and sustainable way (EC 2020, Circular Economy action plan).



Source: International Advisory Council on Global Bioeconomy - Our planet Bioeconomy solutions for global challenges, August 2023

Figure 1. Future positive impact of bioeconomy development from different societal perspectives

The specific bioeconomy strategies and the results achieved in this domain will improve the planet health status of course, but it will also have a positive impact at different levels of community (Figure 1).

Brief literature overview - Modelling approach on circular bioeconomy in agriculture sector

As stated in the introduction part, the interest for analyse the circular economy opportunities exploitation positive impact on the agriculture sector sustainable development and not only, increased especially in the last 10-15 years' period (Rodino et al., 2023). However, regarding the system dynamic modelling techniques applied on agriculture sector there aren't so many publications.

A study performed by Pyka et al. (2021) analysed different approaches on bioeconomy sector through modelling process, presenting a brief bibliometric analysis of published related works, in 2009-2018 period, with the aim of demonstrating the advantages of applying this technique for formulating policy recommendations. The need to approach the subject of the circular bioeconomy in a dynamic perspective is shown in order to formulate policies recommendations regarding possible transition pathways. The authors started from a previous classification (O'Brien et al., 2017), as follows: "economic modeling (computable general equilibrium (CGE) models, partial equilibrium (PE) models), environmental modeling (biophysical and land change models), Integrated Assessment Models (IAMs) and specialist models (or bottom-up models)".

In 2022, authors from Latvian authors (Dolge et al., 2022) published a study regarding the bioeconomy transition pathways identified in their country, in the Green Deal context, using the System Dynamic (SD) approach. The paper presented the conceptual and operational definition of SD in the introductory part, and subsequently presenting the dynamic model focused on Latvia forestry area, but also on agriculture and fishing sectors. The main objective was to find a solution in order to achieve the balance between SGD Development Goals and compliance with the Green Deal mission, on the one hand, and the mentioned sectors economic development. The agriculture model and the causal loops diagrams showed 9 types of cause-effect-cause relationships, such as: "raw material available - production capacity derivatives - raw material available (B1)"; "total available land - land use - total available land (B2)"; "profit per unit land area - indicated land use fraction - profit per unit area (B3)"; "potential land yield - land yield - potential land yield (B4)". Not at least, 4 scenarios were applied using the designed model, following the evolution of several parameters: "added value to turnover ratio", "labour productivity", "energy productivity", "resource productivity", "generated waste". It can be concluded that the best results were obtained by combining all three policy instruments: subsidies, reduction of input costs and the carbon tax.

The paper entitled "*An efficient agro-industrial complex in Almerıa (Spain): Towards an integrated and sustainable bioeconomy model*" (Egea et al., 2018) presents in the introductory part the European legislative framework regarding bioeconomy and circular economy. An integrated model for the Almeria area is proposed, through a biorefinery establishment. The authors presented the arguments that led to this transition path, related both to the specific case study area characteristics and the sustainable development objectives. The model operates with variables like biomass from agricultural activity, especially from the production of fruits and vegetables, the capitalized opportunities offered by applying the circular bioeconomy principles, using statistical data.

The dynamic modelling approach was focused on Sweden agriculture sector, using CLD diagrams (Causal Loop Diagrams), designed in cooperation with experts in the field and validated by stakeholders. CLD is used as an analytical tool to encourage the development and documentation of a qualitative approach to the structural components of conventional economy to circular bio-based economy. 4 types of CLD are presented, entitled "Identification of Dynamics Governing the Expansion and Maintenance of Farming Activities"; "Employment of More Environmentally Friendly Practices in Conventional Agriculture"; "Identification of Dynamics Governing Biomass Availability"; "Introduction to Diversified Farming and Regenerative Production" (Bennich et al., 2018).

Similar methods as above described were also applied in others European projects financed through Horizon 2020 program. For example, during the COASTAL project (under 773782 Grant Agreement) a complex methodology was developed in order to design the most efficient transition pathways to a more ecological, greener version of main economic activity sectors like agriculture, tourism or aquaculture: mapping stakeholder's perception and expertise, design Causal Loop Diagrams, generating Business Road Map, design the SD model, by quantifying the initial CLD (Lazăr L. et al., 2022).

The bases of System Dynamics Modelling - between curricular discipline and practice

From our professional experience during previous research projects (COASTAL, 2018), implementing for first time a methodology using a modelling software programs and others tools and operating with Causal diagram loops or Fuzzy Cognitive Maps, could involve a difficult process and also can represent in a certain point more a barrier rather than a motivation in achieving the expected results. This statement is valid firstly for the researcher but also for the stakeholders or others participants at different brainstorming meetings, in order to design the initial diagram, based on the main synergies between cause or effect variables, regardless from different sectors. Therefore, usefulness of familiarization with certain basic concepts of dynamic approach is explained.

Generally, there are 5 steps in the SD modelling process, starting from the design up to policy recommendation (Figure 2).

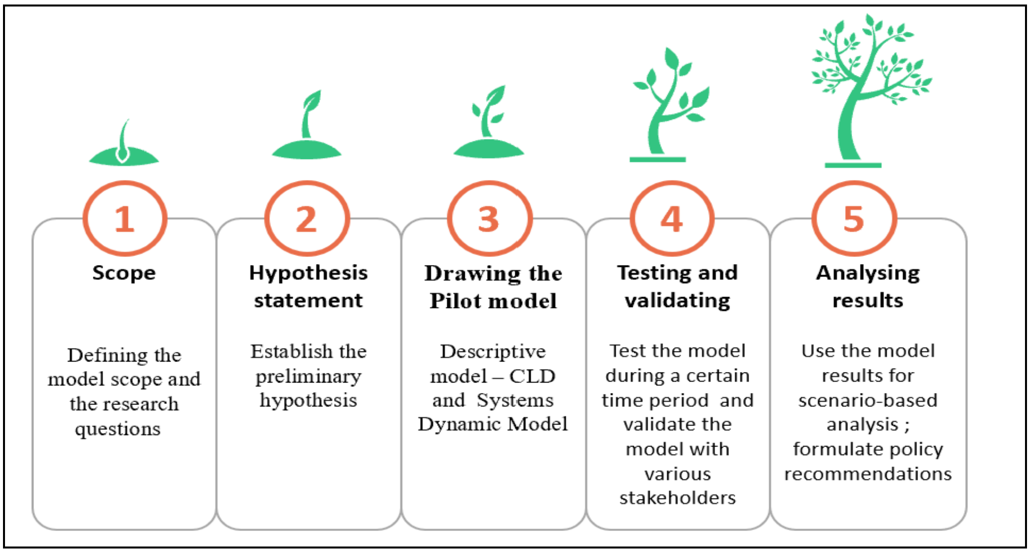
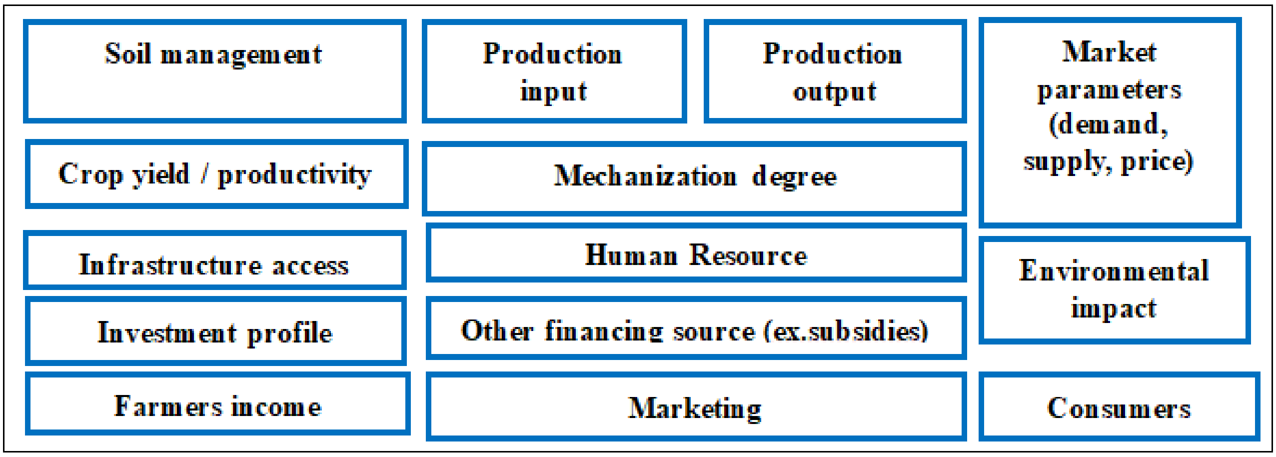


Figure 2. The steps of SD modelling

Starting from this consideration, this research aims to develop a dynamic methodology, in order to develop an accurate, valid and functional model, for improving the integration of bioeconomy principles at the level of farm management, in order to contribute on natural resource conservation but without harming the farmer's incomes level.

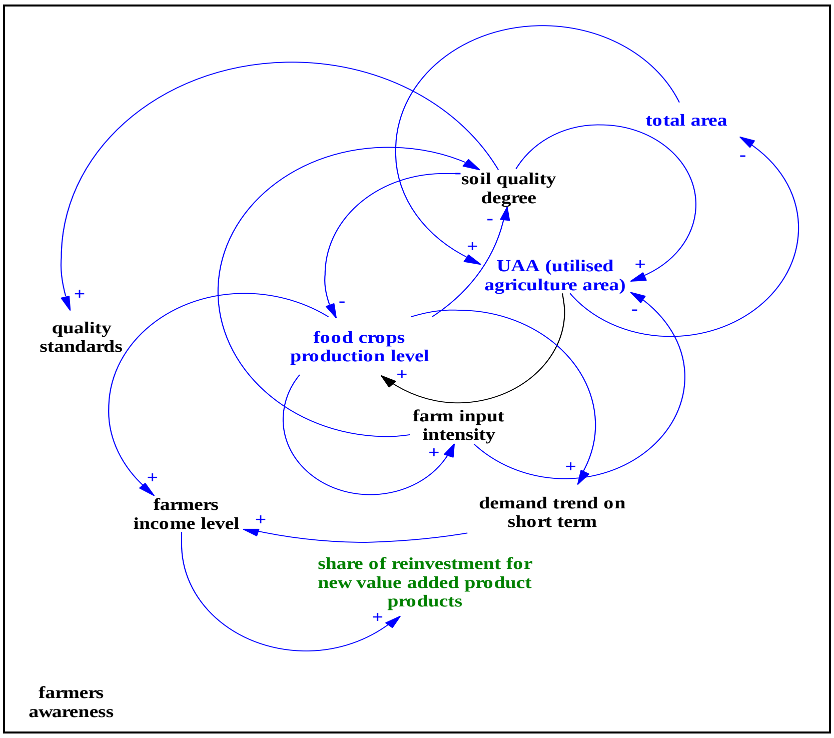


Source: Authors processing on literature overview (after Blumberga et al., 2017)

Figure 3. A simple structure of generic model with several variables type level

With others words, our main goal of modelling activity is obtain a measurable response at the following question: what share of profit is feasible to be reinvested in a new biotechnology development and implementation production, for by-products resulted from food crop production, from farmers but also from the decision-makers point of view? policy makers, researchers and others) in order to create knowledge transfer networks. The public authorities will associate the new product sustainable characteristic with the environment status, if is positively changed. On the other hand, the producer will associate the same characteristic with the financial parameters status. Thus, the main challenge is to identify a value of the main variables, in order to ensuring the balance between both perspectives. In fact, latest approaches of European Commission encourage the interconnection between stakeholders of different area (farmers, fishers, business actors, academic figures, NGO's representatives.

According to Blumberga et al. (2017) the modelling activity of dynamic systems should start with a simple, generic model, which includes the main dynamic variables of the model. Figure 4 presents an option for the generic model useful for the present research aims. Once the generic structure model is set, several types of variables can be added in order to establish the main synergies between them, as well as the main cause-effect relations.



Source: Authors processing in Vensim (Sapiri et al., 2017)

Figure 4. Causal loop diagram regarding the land use implication regarding the farmer's income

Drawing firstly the descriptive model in the form of a causal loop diagram (CLD) is useful in identifying and understand the feedback relationship between variables and links. Thus the initial system can be placed in a cause-effect matrix. The arrows show the positive (or self-reinforcing) and negative (or self-correcting) loops, or, in other words, they show if the one variables directly influence in the same way or opposite. When a system component is linked through a series of other variables to itself, it can be call "feedback loop". Further, feedback loop specific is often divided in balancing and reinforcing loops (Sterman, 2000).

For instance, taking into consideration the first level of the structure model, the soil management, a simple example for CLD is shown in Figure 4. Even if the examples given in Figure 3 is simple, rather logic than complex, several types of loops of different typology's can already be observed. The balancing loops neutralize the effect with a link in opposite direction. Reinforcing loops occurs when changing one direction involves a recalibration of the links between variables. In this case, introducing the variables of share of reinvestment for new value-added products acts as a solution in order to increase the farmer's income and to improve the soil quality, which decreased due to a high intensity of using farm input, in order to have better crop yield and higher incomes. Therefore, it can be stated that a system dynamics simulation model for a circular farming system in the vegetable sector aims to develop a representation of the circular farming system that includes the cultivation, processing and use of agricultural products in a closed economical loop. The research questions should address the main factors influencing field crop productivity, the quantification of these factors, and their impact on farmers' incomes. We propose several key components and variables related to cultivation and harvesting of crops, processing and value added, use of locally available resources and circularity and waste reduction (Figure 5).

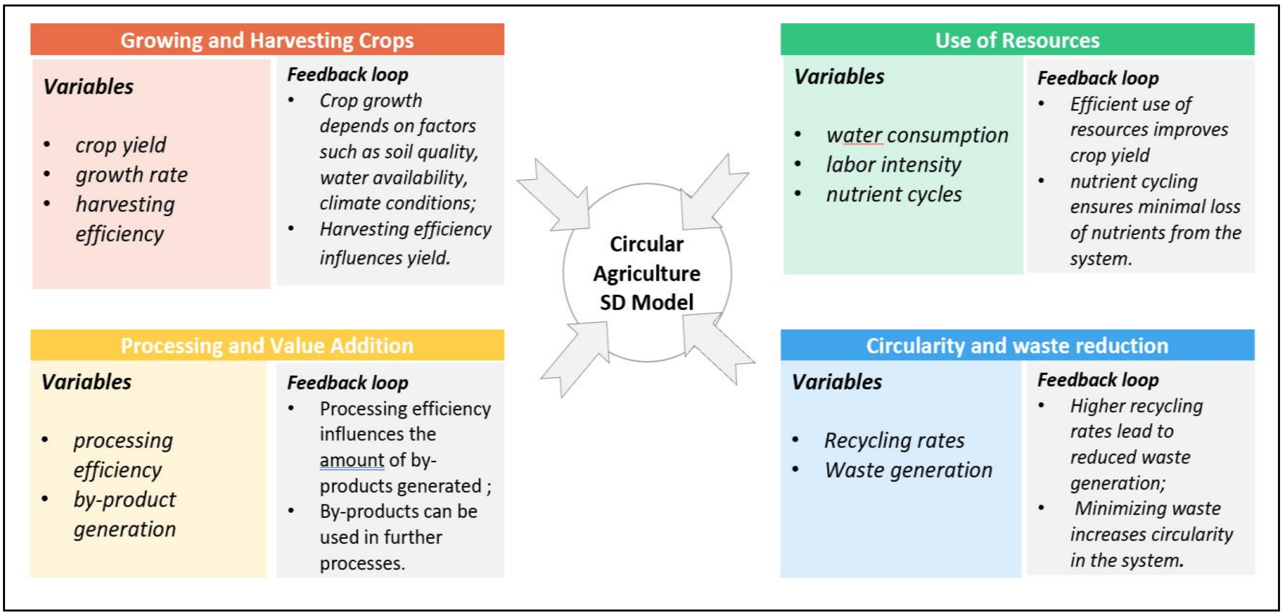


Figure 5. Key components of a Circular agriculture SD model

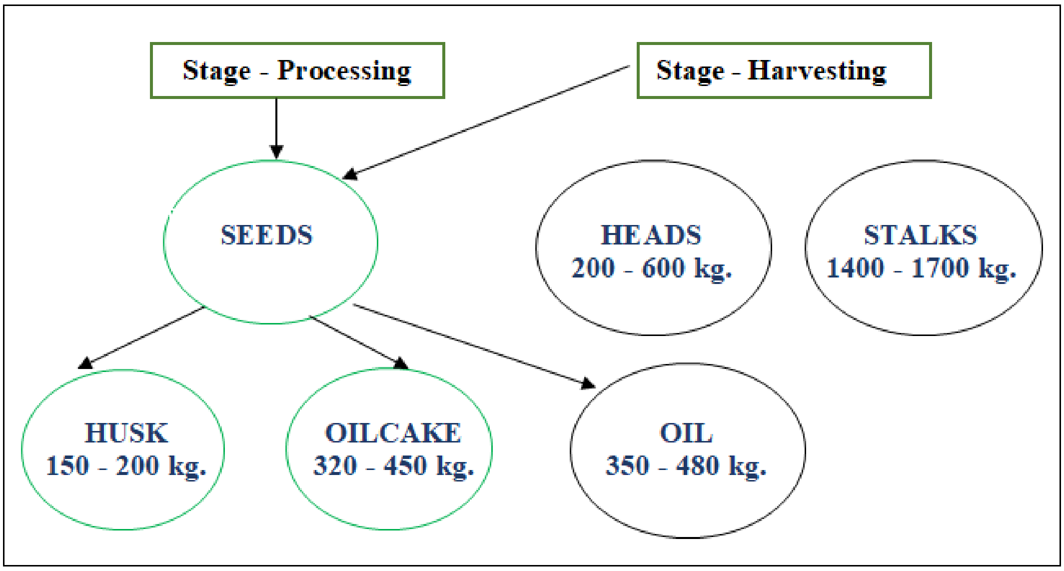
As described before, a causal loop diagram illustrates the relationships between different variables in the system and the feedback loops that influence them. For instance, in a circular agriculture model, an increase in crop yield may positively impact economic viability, but it could also lead to increased volumes of waste if processing efficiency and updated technologies for reuse are not carefully observed.

For future research directions we propose a pilot system dynamic model on developing new value-added products from sunflower production. The sunflower crop was selected due to multiple considerations.

Firstly, Romania is among the main sunflower producers in Europe. This crop is widely spread on Romanian agricultural fields due to favourable climatic conditions and soil quality, which allow obtaining high yields (Duca et al., 2022). According to National Institute of Statistics data (Tempo Online, 2023), the sunflower yield reaches 1.93 tons/hectare, which generates substantial seeds production for Romania (2.1 mil. tons in 2022). In addition to economic aspects, sunflower cultivation also contributes to the diversification of the agricultural system, ensuring an efficient crop rotation and improving soil fertility (Joiţa-Păcureanu et al., 2023).

Secondly, sunflower cultivation and production generates different category of by-products, very valuable for generating value-added products.

The average potential of biomass content at the sunflower level (Figure 6), depending on moisture content, soil type, hybrid and sowing time was estimated at around 7% for one tone of seeds (Geletukha et al., 2020; Partal, 2022). The utilization of sunflower by-products in other industrial flows extends the way for advancing circular economy principles across various sectors. Sunflower hulls, representing a significant share of the sunflower seed weight, have significant protein content after dehulling, thus generating an opportunity for alternative protein sources in animal feed (Karkelanov et al., 2020; Alharthi et al., 2021). Sunflower oil cake, a by-product resulted from the oil extraction process, was demonstrated as high-protein feed source and a good substrate for enzyme production, indicating its potential in circular economy applications (Egea et al., 2021).



Source: Authors processing on literature overview (after Geletukha et al., 2020)

Figure 6. Sunflower potential biomass level, depending on the production stage

Sunflower was already studied as a renewable source for biofuel production, namely for biodiesel (Havrysh et al., 2023). Some proteins isolated from sunflower by-products exhibited bioactive properties, making them suitable for food industry as functional ingredients (Egea et al., 2021; Petraru et al., 2021). Phenolic compounds extracted from sunflower seeds can be transformed into protein isolates for edible films, contributing to sustainable food packaging solutions (Saha, 2015; Ancuţa and Sonia, 2020).

Sunflower stalks are rich in cellulose and lignin, thus providing a raw material source for bio-composite materials, thermal insulation, paper production and fuel, aligning with the growing demand for sustainable materials. Furthermore, the extraction of natural dyes from sunflower petals offers environmentally friendly alternatives for textile dyeing. Sunflower production waste can also be used for composting (Marechal and Rigal, 1999; Nedelcu et al., 2018; Oyeleke et al., 2022; Yang et al., 2023).

Others research outcomes empathize with the idea that the problems related with the energy security is the main determinant factor of green technologies transition, consequently the by-product obtained from sunflower seeds production should be used as a responsive solution for this problem (Havrysh et al., 2023). Overall, the diverse applications of sunflower by-products highlight their significance in promoting circular economy practices.

CONCLUSIONS

In conclusion, the exploration of bioeconomy and circular economy concepts, along with their legislative frameworks, has become increasingly significant in recent years. Research in the field of bioeconomy, particularly in agriculture, has seen significant growth, although with a relatively small number of publications employing system dynamic modelling techniques. However, several studies demonstrate the potential benefits of employing such models for formulating effective policies and transition pathways towards a circular bioeconomy.

The implementation of system dynamic modelling at the farm management level presents both challenges and opportunities. While it may initially be daunting for researchers and stakeholders, familiarization with the basic concepts of dynamic modelling is crucial for effectively addressing complex agricultural issues.

Models like causal loop diagrams help identify feedback relationships and understand the interconnectedness of variables, aiding in the formulation of policies that promote sustainable agricultural practices while maintaining farmers' incomes. In dynamic systems modelling, Policies, Structures, Information, and Ideas (PSII) are central to understanding and analysing complex systems, allowing researchers to identify and explore the interactions between different components of a system. Policies represent the decisions and actions taken by the actors involved in the system, and structures refer to the relationships and connections between these decisions and the results obtained. Information includes the data and knowledge available about the system, while ideas represent the beliefs, values, and perspectives that influence how policies are formulated and implemented. Together, these four elements form a comprehensive framework for the dynamic analysis of systems and for identifying potential interventions to improve the performance and resilience of systems in the face of change and disruption.

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