Circular Economy and Sustainability (2026) 6:19
https://doi.org/10.1007/s43615-026-00822-5

ORIGINAL PAPER

The Impact of Digitalization on Circular Supply Chain Performance in the Agricultural Sector: A System Dynamics Approach

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Received: 4 January 2025 / Accepted: 14 September 2025

Abstract
Over the past decade, environmental challenges and disruptions in the ecosystem have increasingly highlighted the need to assess the effectiveness of circular supply chain management. Particularly, the escalating per capita consumption of plastics in the agricultural sector, coupled with the resulting environmental issues, underscores the urgency of evaluating supply chain management practices within the plastics industry. The objective of this research is to explore the impact of digitalization on the performance of circular supply chain management in the plastics sector. The statistical population for this study consists of the plastics industry within the agricultural sector. A purposive sampling method was employed in this research. This study is classified as applied research and adopts a descriptive-analytical approach to data collection. In terms of data type, the research is quantitative, and it adopts a cross-sectional design to examine data at a specific point in time. A system dynamics approach was utilized to develop the model and analyze the data. Specifically, this research investigates the influence of Internet of Things (IoT) technologies and transportation system management on the performance of the circular supply chain. The findings of this study reveal that transportation management platforms, enabled by IoT networks, not only optimize logistics by eliminating queues and obstacles but also support environmental sustainability by minimizing waste.

Keywords Supply chain · Circular economy · Plastics industry · System dynamics

Introduction

The global population, having surpassed 8 billion, is projected to reach approximately 10 billion by 2050, intensifying the challenge of ensuring global food security. While innovations in agricultural technologies over the past two decades have augmented the Earth's

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capacity for food production, agriculture remains a significant contributor to environmental degradation, often conflicting with the United Nations Sustainable Development Goals (SDGs). According to the IPCC [1], global warming caused by human activities of 1.1 °C has caused changes in the Earth's climate that are unprecedented in recent human history. The organization previously reported that agriculture, forestry and other land uses account for approximately 23% of the world's total anthropogenic greenhouse gas emissions.

FAO [2] reports the agricultural sector accounts for about 30% of global energy consumption and over 70% of freshwater withdrawals, and is a major driver of deforestation and land-use change, particularly in the tropics. These activities are inextricably linked to global warming, which negatively impacts crop yields and increases the risk of food insecurity. As The State of Food and Agriculture [3] demonstrated, agri-food systems activities generate significant benefits for society, but also have negative impacts on economic, social and environmental sustainability. The State of Food and Agriculture [4] provides in-depth assessments of value chain contexts, highlighting the economic, social and environmental impacts of current practices to guide policy interventions.

In recent decades, plastics have become increasingly integral to modern plant agriculture. However, the short-term benefits derived from their utilization should not compromise long-term sustainability objectives [5–7].

Annual per capita plastic waste generation varies considerably, ranging from 221 kg in the United States and 114 kg in OECD and European countries, to an average of 69 kg in Japan and Korea [8]. Within continental Europe, approximately 40% of consumed plastic is recycled, with the remainder being incinerated or entering waterways and soils, revealing a considerable disparity in regional practices. Certain European nations continue to rely predominantly on disposal practices, with minimal emphasis on recycling [9]. Agricultural activities constitute one of the primary pathways for plastic entry into soil ecosystems. According to the Food and Agriculture Organization (FAO), plastics utilized in agriculture account for 3.5% of total global plastic production. While this may appear to be a modest proportion, this figure translates to approximately 12.5 million tons annually. Critically, these estimations do not include food packaging, which accounts for an additional 37 million tons of plastic per year [10]. The excessive use of plastics has well-documented detrimental effects on wildlife and human health. Accordingly, plastic recycling assumes paramount importance, offering a substantial avenue for mitigating environmental pollution and preserving natural resources. Given the inherent recyclability of plastics and many of their derived materials, effective collection and recycling efforts are crucial. The current lack of facile, scalable, and environmentally benign recycling processes has hindered global plastic waste recycling rates, with only an estimated 9% of plastic being recycled. The confluence of high production rates of non-biodegradable plastics, the associated landfill waste, and rapid population growth underscores the unsustainability of the traditional linear economy model, predicated on the extraction, production, use, and disposal of raw materials.

Sustainable Supply Chain Management (SSCM) has garnered increasing attention as a significant and growing area of research. This concept plays a pivotal role in enhancing organizational sustainability [11–14]. Organizations are increasingly integrating sustainability considerations into their decision-making processes, both short-term and long-term, within the realm of supply chain management [15, 16]. Studies by researchers such as Carter and Rogers, Seuring and Müller, and Ahi and Searcy, through providing comprehensive definitions of sustainable supply chain management, have underscored the importance of integrating sustainable development programs with supply chain management to achieve organizational goals [15–17].

In line with previous research, sustainable supply chain management (SSCM) encompasses economic, environmental, and social objectives simultaneously. Scholars such as Seuring and Müller [15] and Genovese et al. (2017) have highlighted the importance of integrating sustainability considerations into all stages of the supply chain. Circular supply chains, a subfield of SSCM, focus specifically on closing resource loops through recycling and reuse strategies. Recent literature emphasizes the growing relevance of digitalization, particularly technologies such as IoT, AI, and block chain, as enablers of transparency, traceability, and real-time decision-making in circular supply chains. However, the application of these digital tools within agriculture-related plastic recovery systems remains underexplored.

Furthermore, changes in the business environment, including evolving customer demand patterns, intensified competition, and pressures from stakeholders, have led organizations to adopt sustainable practices in their supply chains [18]. Additionally, the need for effective engagement with key stakeholders within the supply chain to strengthen sustainability approaches has become increasingly recognized [19].

The concept of the circular supply chain can be explained within the paradigm of the circular economy. The circular economy is defined as an economic model aimed at eliminating waste and optimizing resource utilization. Within this paradigm, circular systems, of which the supply chain is a component, pursue closed-loop cycles through strategies such as reuse, sharing, repair, remanufacturing, and recycling. This aims to minimize resource consumption, waste generation, pollution, and greenhouse gas emissions. The fundamental strategy of these systems is to maintain materials, products, equipment, and infrastructure within the consumption cycle for an extended period. This strategy necessitates the application of techniques and methods appropriate to the type of product and service. The circular supply chain is emerging as a comprehensive approach at a global level, and organizations are increasingly seeking to implement sustainability in their supply chains. While some organizations focus on waste reduction and greenhouse gas emissions, leading organizations pursue broader goals, such as improving energy efficiency, utilizing sustainable packaging, and promoting workforce health and well-being [20].

Digitalization and automation, as the most crucial foundations of the significant industrial transformation known as the Fourth Industrial Revolution, lead to agility, flexibility, transparency, and the possibility of appropriate and reliable decision-making [21]. In conjunction with the rapid growth of internet-based technologies and the widespread application of information technology, production operations and processes will benefit from features such as adaptability, resource efficiency, the design of machinery and production systems compatible with human ergonomics, as well as integration with customers and business partners in order to develop value-based businesses [22].

The utilization of digital communication technologies among supply chain partners improves the levels of control in inter-organizational collaboration and reduces mistrust [23]. The ability to monitor operations in real time highlights the role of responsibilities and supervision, and allows for direct control over the performance of suppliers, from the stage of providing the necessary resources and raw materials to the delivery of the required goods to buyers. Achieving such an environment necessitates the development of electronic infrastructures that enable data and information sharing across operational sectors in the supply chain [24]. The digitalization of the supply chain has not only led to the integration of processes and the elimination of boundaries, but has also had positive effects on efficiency and coordination within the supply chain. These developments allow organizations to face everyday challenges and achieve greater productivity through intelligent decision-making.

Despite innovations in circular economy practices, integrating digital technologies such as Internet of Things (IoT) and smart transportation systems into circular supply chains has received limited attention in existing literature. While existing studies have broadly addressed sustainability in circular supply chains, there is a lack of specific focus on how digitalization can influence operational performance indicators such as carbon footprint, operational cost efficiency, and supply chain lead time, especially in the context of agricultural plastics, where logistics and waste collection dynamics are highly complex.

The absence of comprehensive frameworks for assessing the operational and environmental benefits of digitalization in circular supply chains represents a significant research gap. As global supply chains increasingly face pressures to adopt sustainable practices, it is essential to understand how emerging technologies like IoT, smart logistics, and data-driven systems can improve efficiency, reduce emissions, and minimize waste. Moreover, little is known about the dynamic interdependencies between technology adoption levels and performance outcomes in circular models, which makes it difficult for managers and policymakers to design effective digital transition strategies.

To address these gaps, this study develops a system dynamics model to evaluate the impact of digitalization on the performance of circular supply chains for agricultural plastics. Then, scenario analyses are conducted to explore how different levels of IoT adoption and smart transportation capabilities influence these performance outcomes, providing practical insights for improving circular economy operations and informing future digital supply chain strategies.

The main focus of this study is to investigate how digitalization technologies impact the performance of the circular supply chain in the agricultural sector. By addressing this question, it can be asserted that this research is innovative in terms of the integrated application of digitalization technologies in the circular supply chain management of the plastics industry within the agricultural sector, using a system dynamics approach.

The remainder of this research is organized as follows: After the introduction, the second section reviews the theoretical foundations of the role of plastics in the agricultural sector, the circular economy, and the circular supply chain. The third section introduces the research methodology. In the fourth section, the model design and scenario development will be carried out. The research findings are then presented, and finally, conclusions and suggestions for managers and researchers are provided.

Therefore, this study aims to answer the following central research question: How do digitalization technologies affect the performance of circular supply chains in the agricultural plastics sector? Sub-questions include: (1) What role do IoT and intelligent transport systems play in improving material recovery and recycling efficiency? (2) How can system dynamics modeling support decision-making in circular supply chain management? The objective is to develop a dynamic simulation model that captures the key interactions and feedback loops among production, distribution, and recovery processes, with a focus on digital enablers.

Research Literature

Role of Plastics in Agriculture

Plastics offer numerous environmental and social benefits in agriculture. Plastic mulch films, which constitute 50% of all agricultural plastics, are widely used in crop production. These films provide significant agronomic advantages, including weed and pest control, soil moisture conservation, regulation of soil and air temperature, and increased nutrient uptake. These benefits collectively lead to higher yields, improved water and nutrient use efficiency, and reduced pesticide application. Moreover, the increased soil temperature under plastic mulch allows for earlier planting and harvesting, which provides market advantages. Plastic mulch films are also valuable in organic farming, as they suppress weeds and insect infestations without the need for synthetic pesticides.

Plastics have diverse applications in agriculture and farming. They contribute to reducing the demand for irrigation water, pesticides, and fertilizers, resulting in decreased greenhouse gas emissions and increased crop yields, thereby impacting several United Nations Sustainable Development Goals. However, incidental plastic pollution in agricultural lands is also a concern, with multiple sources [25]. Conventional plastic mulch films are typically made of low-density polyethylene (LDPE), but they can also be composed of other polymers such as PVC or ethylene-vinyl acetate copolymers. Incomplete collection of these films after use leads to the accumulation of persistent plastic residues in the soil. Additionally, chemical additives can leach from mulch layers. Consequently, repeated mulch applications can result in the accumulation of plastic residues and released additives, which can have detrimental effects on soil productivity and soil health. Certified biodegradable soil mulch films are marketed as an alternative to conventional thin mulch films. These biodegradable options can be plowed into the soil after harvest, where they completely decompose into carbon dioxide and microbial biomass under anaerobic conditions [26].

Plastic sheets are standard covering materials in greenhouses and high and low tunnels, providing thermal insulation, absorbing radiant energy, and offering protection against weather and pests. These sheets are manufactured from a wide range of polymers and contain additives that provide diverse optical and energy properties. Plastics are also utilized as shade and protective nets, such as sunshades and hail protection, and as seedling supports [27]. Water scarcity is a major factor limiting crop growth and yield. In addition to mulch films, irrigation pipes and drip tapes help deliver precise amounts of water directly to plant roots, improving water use efficiency. Irrigation equipment is typically made from common polymers like high-density polyethylene (HDPE). Seedling and potting trays are widely used in crop production. Seedling plug-in trays facilitate effective germination and optimize plant growth. Furthermore, some crops require support during cultivation. Potting trays are used for transportation, and plastics are used in the production of agricultural packaging materials, such as fertilizer and storage bags, flexible bulk containers, boxes, and pesticide containers. While this review focuses primarily on field applications, various plastics are also used in hydroponic and indoor vertical farming systems for pipes, clamps, grow trays, nets, packaging, and mesh pots [28]. Sustainable use of plastics in horticulture necessitates prioritizing reuse and recycling over post-use disposal.

Further research is needed for plastic applications that currently lack recyclable end-of-life processing options. In addition to these principles, two key criteria can guide sustainable use strategies and the identification of post-use processing options for plastics in agriculture: (1) the collectability of the plastic after use and (2) the duration of its use. For applications that allow for complete post-use collection, reuse and recycling are the preferred processing options, regardless of the duration of use. In such cases, sustainability can be enhanced by utilizing chemically and weather-resistant plastics and by implementing technologies that ensure complete post-use collection, especially for plastics used below ground, such as irrigation pipes [29].

Circular Economy

The idea of circular flows and systems as a research field has gained attention in the last decade and is growing rapidly [29]. The concept traces its roots back to Boulding in 1966 [30]. Although Boulding used the precise term "circular economy", he referred to "cyclic ecological systems" without which human survival on Earth would not have been possible in the long term [31]. Building on Boulding's ideas, the introduction of the term circular economy is most likely attributed to Pearce and Turner in the late 1980 s and early 1990 s [32]. Based on research on the impacts of linear and open systems, they argued that a traditional linear economy should be replaced by a circular system in which waste becomes an input to the system [33, 34].

Considering the origin of the actual concept of circular economy and its application in practice, it is necessary to consider related concepts, frameworks and research streams that are more or less related to circular economy, such as industrial ecology, performance economics, water economics, etc. Regenerative design Since the concept of circular economy has a background in different historical, economic and environmental fields [35], it is difficult to achieve an interdisciplinary understanding, which leads to different definitions, domains and narratives of circular economy in research and practice [36]. There is agreement among researchers that there is no consensus on the definition of circular economy, which is of great importance to the scientific and practical communities [37].

Circular economy is considered as a continuous positive development cycle that preserves and enhances natural capital, optimizes resource efficiency and minimizes system risks by managing finite reserves and renewable flows. It works effectively at any scale. This economic model seeks to decouple global economic development from the consumption of finite resources.

The European Commission [38] states that in a circular economy the value of products and materials is maintained for as long as possible. Waste and resource use are minimized and when a product reaches the end of its life, resources are kept in the economy to be used again and again to create more value. The European Parliament's research [39] states that the circular economy is a production and consumption model that involves the reuse, repair, refurbishment and recycling of materials and products. Kircher et al. [36] define the circular economy as an economic system that replaces the concept of "end of life" with the reduction, reuse, recycling and recovery of materials in the production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), the mess level (eco-parks) and the macro level (city, region, country and beyond) with the aim of achieving sustainable development and thus creating environmental and economic quality at the same time. Achieving a circular model requires cyclical and regenerative environmental innovations in how society regulates, produces, and consumes.

Circular Supply Chain Management

The integration of circular economy into supply chain management has been called circular supply chain in previous literature. Circular supply chain management is the integration of circular thinking into supply chain management and its surrounding industrial and natural ecosystems that systematically recycles technical materials and regenerates biological materials towards a zero-waste landscape through system-wide innovation in business models and supply chain operations. Product/service design through to end-of-life and waste management, and involves all stakeholders in a product/service. The life cycle includes component/product manufacturers, service providers, consumers and users [40]. Circular supply chain management can be applied to manufactured products as well as service products, and organizations collaborate with others both internally and externally. This section presents a promising perspective to guide supply chain managers to achieve successful performance in resource efficiency and thus profitability, while simultaneously minimizing negative environmental, social and economic impacts.

Digitalization and its Role in Circular Supply Chains

In the current environment, our interaction with the physical world is rapidly changing due to technological advances. Companies must adopt new technologies to achieve economic, environmental, and social goals essential for sustainable development and implementing a circular economy. To effectively pursue these goals, circular supply chains should leverage digital technologies, particularly for managing reverse flows in line with international frameworks. Digitalization is a game-changer; it can ensure environmental, social, and economic benefits. The circular approach is closely tied to technology, especially when products and their components are designed for reuse and waste reduction.

The circular economy is defined as regenerative by design and has garnered significant attention from researchers and policymakers. With the rise of digital technologies like big data and the Internet of Things, this study explores how these technologies can facilitate the transition to a circular economy. Through 4G technologies, products communicate with consumers, sending signals to companies about their performance, usability, and obsolescence.

A review reveals that research in this area is scattered across interdisciplinary fields, covering: (a) digitalization technologies and the circular economy; (b) barriers to a digitalization-based circular economy; (c) enablers of a digitalization-based circular economy; (d) digitalization technologies and circular supply chain management; and (e) the impact of digitalization on the performance of circular supply chain management. Recent concerns about the circular economy and digitalization challenges have generated significant interest in taking necessary actions to address these challenges. A comprehensive literature assessment underscores the importance of evaluating the enabling role of digitalization in the transition to a circular economy.

As summarized in Table 1, previous studies predominantly addressed sustainability performance in agri-food supply chains using decision-making or statistical modeling techniques, with a limited focus on system dynamics applications. Moreover, digitalization tools such as IoT and smart logistics systems have not been incorporated into these models. This study contributes to the literature by developing a system dynamics model that simulates

Table 1 Comparative summary of related studies

Study	Sector	Method	Performance Criteria	Key Findings	Identified Gap
Kumar et al. [45]	Agri-food	MCDM	Sustainability indices	Identified drivers of circularity	No system dynamics or digitalization focus
Yontar & Ersoz [46]	Food SC	SEM	Economic, environmental, social	Evaluated sustainability in food SC	No operational modeling or scenario analysis
Kazancoglu et al. [47]	Food SC	System Dynamics	Reverse logistics efficiency	Modeled closed-loop SC	No digitalization elements
Yontar & Ersoz [48]	Fresh Food	SEM	Sustainability performance	Assessed performance indicators	Lacks operational system modeling
Bag et al. [49]	Firms in high-carbon sectors	SEM	Sustainability and resilience	Evaluated sustainability in food Circular SC	No system dynamics or scenario analysis
Duan et al. [50]	SEMs	TOPSIS	Environmental Sustainability	connect well-known digital to the infrastructure of sustainable circular supply chain	
Dong et al. [51]	Agri-food industries	PLS-SEM	Profitability and Sustainability	The Digitalization Impacts on Agri-Food Supply Chain	
Liu et al[52]	Industries	SEM	performance	Digital technologies and circular economy in supply chain management	Lacks operational system modeling
This Study	Agricultural Plastics	System Dynamics	Cost, lead time, carbon footprint	Analyzes digitalization scenarios in CE context	New sectoral focus and IoT integration

the operational and environmental performance of circular agricultural plastic supply chains under various digitalization scenarios.

From the above theoretical and empirical literature, the following gaps are clearly visible. Most previous research focuses on the impact of digitalization on supply chain performance or on the importance of the relationship between digitalization and the circular economy. Most of these studies have also been conducted in the manufacturing sector and their analysis techniques have also been statistical techniques or multi-criteria decision making. Instead, this research seeks to investigate the impact of digital technologies on circular supply chain performance with a system dynamics approach in the agricultural sector and is innovative in terms of applying the concept of systems thinking and developing a dynamic model of the integration of digitalization and circular supply chain. It is also innovative in applying that model to the agricultural sector and in scenario building to analyze the behavior of agricultural circular supply chain performance under the influence of digital technologies over a long-term time horizon.

Research Methodology: A System Dynamics Modeling Approach

The main objective of this research is to emphasize providing practical solutions to the problem of plastic consumption management in the agricultural industry. This research, with an emphasis on solving an applied problem and providing a solution for circular supply chain management in the plastics industry, is developmental-applied research from the perspective of the objective and a descriptive-survey from the perspective of the data collection method. Two common methods in research to collect the necessary information are library and field research. In this research, by examining theoretical frameworks and empirical background, the policies and variables of the circular economy model of the system dynamics are determined. Also, expert opinions and secondary data are used to determine the data related to the model parameters. Then, the cause-and-effect models and the flow state were designed using Vensim software. In the next stage, the model is validated structurally and behaviorally. Then, scenario analysis will be performed using circular economy policies in the model. Finally, solutions were presented.

The system dynamics approach is designed to help people understand the mechanisms in complex systems that drive their behavior. Through computer simulation, it can connect a set of fundamental feedback structures to a desired behavior observed in the real world and intervene to change the behavior of the system. Policy insights and policy implementation can be identified and tested in coordination with stakeholders and other actors in the system [39]. System dynamics is a discipline that can be viewed in many ways. For some observers, it is a method for building a specific type of computer simulation model. For others, it is an attempt to apply control engineering ideas to socio-economic problems. For many people in society, system dynamics offers unique insights into the behavior and properties of complex systems. For some people, it is a combination of some or all of the above, while others see it differently. Any attempt to constructively and positively examine system dynamics must begin with an acknowledgement that there are many perspectives on the subject [42].

A correct definition and precise demarcation of the problem improves the modeling process of a dynamic system. A review of previous theoretical and empirical foundations and expert opinions in this field can be very helpful. To identify and define the problem, it is necessary to define the behavior of key variables over an appropriate time horizon by reference models. A reference model represents the behavior of the problem over time. The next step is to develop a theory called a dynamic hypothesis, which is based on the behavior of the reference state over a time horizon. The goal of dynamic hypotheses is to identify the structure of the level, flow, and feedback variables that can best explain the problematic behavior [41]. Causal loop diagrams emphasize the feedback structure of a system. Cause-and-effect diagrams are a flexible and useful modeling tool for diagramming the relationship and feedback structure of systems in each part. They show the interaction of positive and negative feedbacks through causal or feedback loops. Flow state diagrams (stockpile and flow) emphasize the underlying physical structure of a system. The change in the level of stockpile over time shows how the operator's decision rules can drive the dynamics of a system [44].

After developing the model and creating state and flow diagrams and before analyzing the results and scenario planning, some validation tests are always performed on the system dynamics models to ensure the validity and accuracy of the model under different conditions. The validation of system dynamics models is based on their convenience and applicability, and their behavior should be reliable under limited and constrained conditions for a specific purpose [43]. Vensim is one of the reputable software in the field of systems thinking fundamentals and systems dynamics methods that has been used in this research. This software is used to simulate and optimize the system performance in reality. This software is a visual modeling tool that provides users with features such as modeling, documentation, simulation, analysis and optimization of dynamic systems models.

Findings

In this study, the system dynamics method has been used as a modeling and simulation technique that is suitable for solving complex management issues and long-term problems. This method reveals the dynamics of the variables under study by analyzing the interactions and relationships between physical processes, information flow, and management policies. The system dynamics method uses causal loops to describe the structure of a system. These mechanisms can have negative (balancing) or positive (reinforcing) feedback. A negative feedback loop represents the programming of goal-seeking behaviors, meaning that from a disturbance, the system seeks to return to the existing state. In a positive feedback loop, an initial state causes further increases, indicating the presence of an unstable state.

Causal loop diagrams play two essential roles in the system dynamics method. First, they serve as initial diagrams for hypotheses during model development. Second, they can be used to illustrate a simple model and display the structure of various systems. Initially, the first stage of analysis based on the system dynamics method analyzes the relationships between the operations of various systems and creates a suitable causal loop to represent these relationships. Figure 1 shows the causal loop diagram of the system under study.

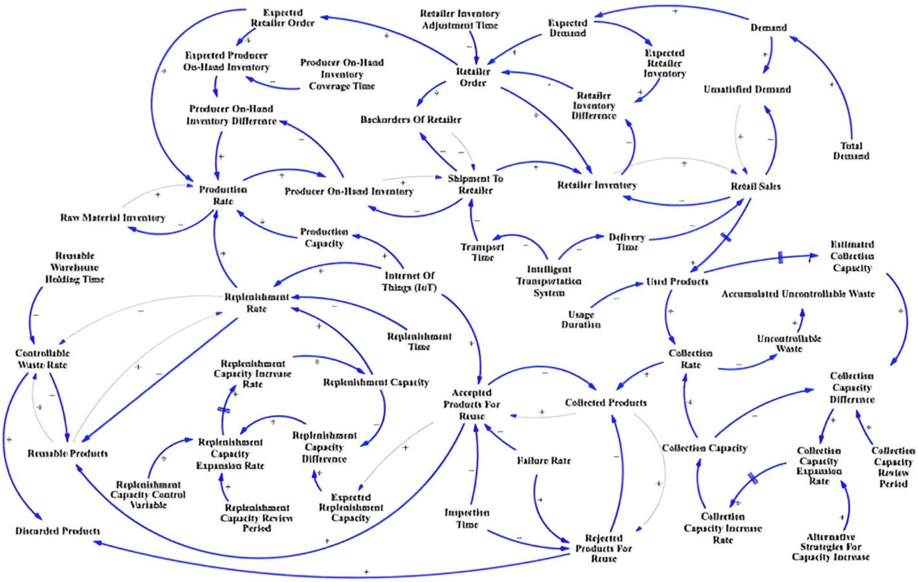

Fig. 1 The Causal Loop Diagram

The arrows indicate the relationships between and indicate the direction of the effect. Also, the “+” or “-” sign at the top end of the effect lines indicates the direction of the effect. The “+” sign indicates a change in the same direction and the “-” sign indicates a change in the opposite direction. It is worth noting that to draw the cause-and-effect diagram and confirm the relationships between variables, the opinions of experts in the plastics industry, theoretical and experimental foundations, and existing documentation have been used. In the following, the mathematical model is presented in the form of a state-flow diagram that shows the model structure and the interrelationships between variables. The state-flow diagram is transformed into a system of differential equations that is solved through simulation. Figure 2 shows the state-flow diagram in this study.

The inventory variables (represented by rectangles) are the state variables, the flow variables (represented by valves) are the rate of change of the inventory variables, and those activities indicate the filling or emptying of the inventory variables. Delay causes a time delay in the content or information channels. In a material output channel, delay is a flow variable. In this model, there are three delays for the product materials used as sales delay, collection capacity addition rate, collection capacity estimate, and expected regeneration capacity.

After the model was built, it was validated. There are many methods for validating a system dynamics model. The boundary adequacy test states whether the main endogenous variables are considered and the time horizon is appropriately considered. The question asked in this section is whether the dimensions of the equations used in the model are consistent with each other? Validation of the model behavior with respect to real data is also important

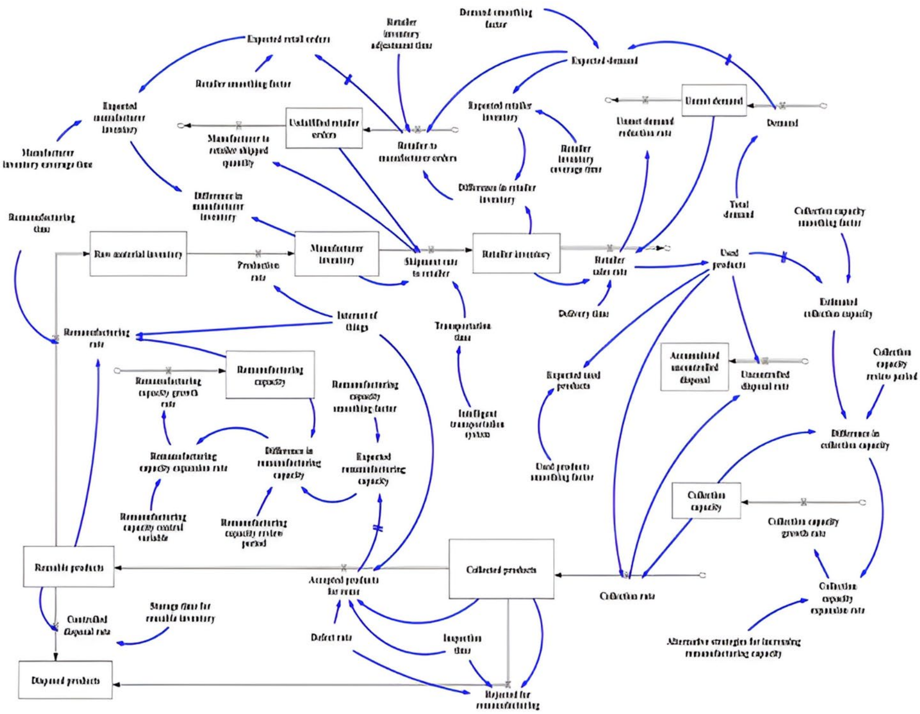

Fig. 2 The Stock and Flow Diagram

and desirable. However, no long-term data compatible with the model time horizon were available. It is also not possible to collect such long-term field data within the scope of this research. Figures 3 and 4 show the structural validation tests performed and confirm that the model structure shows meaningful behavior under parameter values and scenarios. In particular, the model behavior shows significant sensitivity to the parameters of raw materials, production capacity, remanufacturing capacity, collection capacity, digitalization effect, and sales.

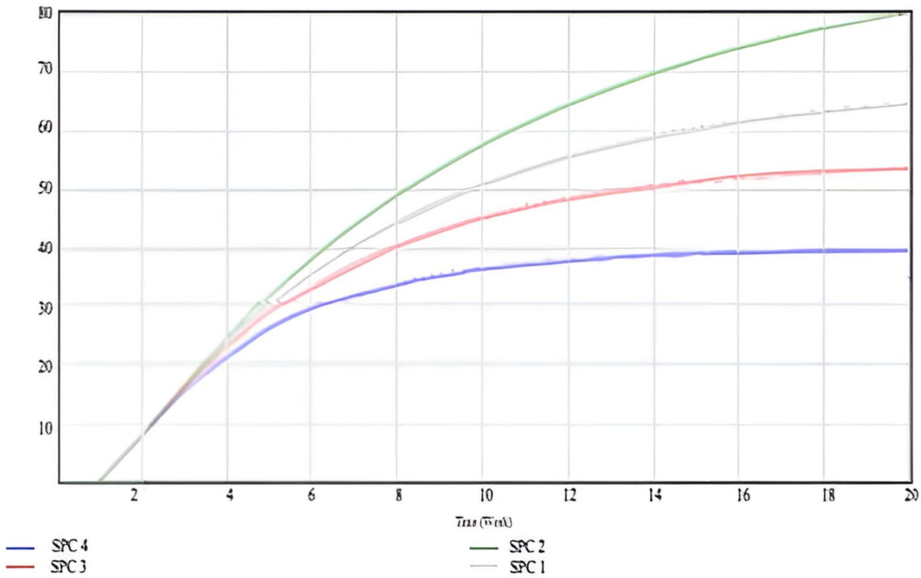

Fig. 3 The Impact of Alternative Strategies to Increase Production Capacity on Collection Capacity

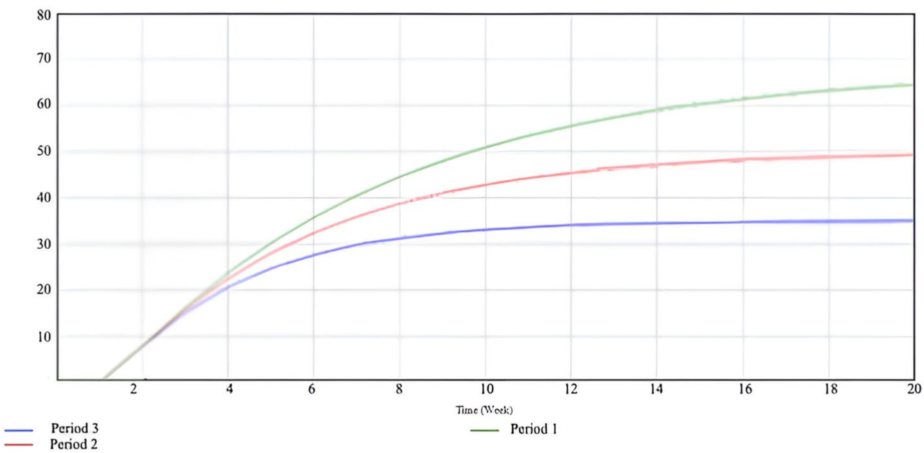

Fig. 4 The Impact of the Collection Capacity Review Period on the Collection Capacity State Variable

Another validation method is the boundary condition test. In this method, the model is subjected to severe conditions to determine how it behaves. In essence, the goal is to ensure that the model does not exhibit strange behavior or fail with large changes in the model parameters. Figure 5 illustrates this test and states that if the retailer's sales rate in the model changes by a factor of 100, the retailer's inventory is expected to approach zero.

After validation and increasing confidence in the model and its calibration, policy analysis should be performed. Policy levers should include the conditions of the basic objectives, along with incentives to achieve the desired results. In this study, three scenarios are designed based on the current situation, the use of intelligent transportation systems and the Internet of Things. Initially, the behavior of the model variables in the current situation, i.e., the lack of use of new technologies, was examined in the form of a zero scenario. Then, the behavior of the variables using intelligent transportation systems in scenario 1 and using the Internet of Things in scenario 2 was examined.

In order to examine the performance of circular plastic supply chain management in the agricultural sector, the behavior of the variables unmet demand, retailer inventory, discarded products, reusable products, collected products, manufacturer inventory and retailer unmet orders was examined. In Fig. 6, the amount of unmet customer demand is observed in three scenarios. In the current situation, the increase in the use of plastic in the agricultural industry is evident, causing the unmet customer demand to increase sharply over time. In Scenario 2, the amount of unmet customer demand is reduced by implementing an intelligent transportation system. The use of IoT, along with an intelligent transportation system in a designed circular supply chain, further reduces unmet customer demand in the agricultural sector.

Figure 7 shows the behavior of retailer inventory levels under three scenario conditions and over time. The use of intelligent transportation systems reduces retail inventory, which reduces holding costs in the circular supply chain distribution system of the plastics industry. As seen in Scenario 2, the plastics retail industry increasingly needs to use the Internet of Things in its operations to improve efficiency, reduce costs, and enhance the customer experience. IoT technology allows retailers to track inventory levels, monitor product per-

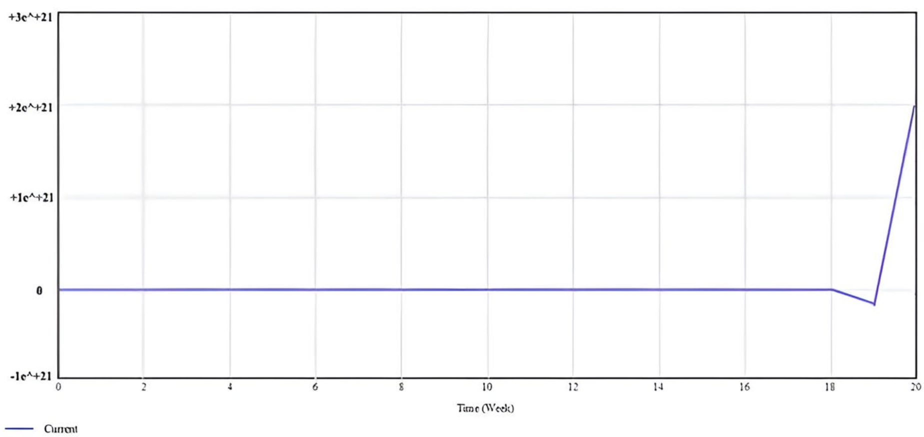

Fig. 5 The Effect of a 100-Fold Increase in the Retailer's Sales Rate

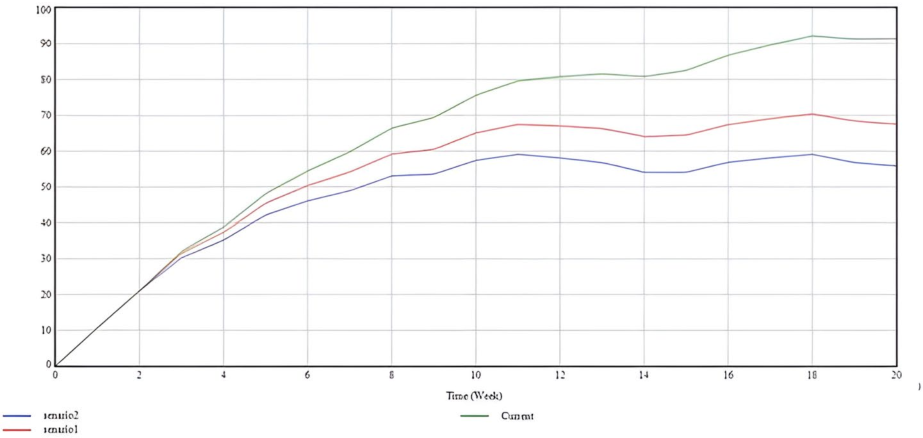

Fig. 6 Unmet Demand

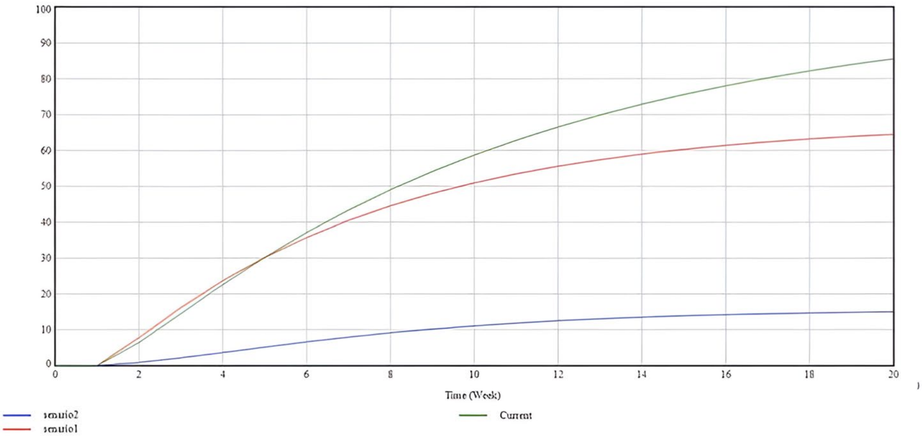

Fig. 7 Retailer's Inventory

formance, and collect data on customer behavior in real time. In addition, they optimize their supply chain and personalize the shopping experience for customers.

Figure 8 shows that the current situation of reusable products in the plastics industry related to the agricultural sector is not favorable. It is also clear that the use of intelligent transportation systems will not have much impact on the amount of reusable products. This graph shows the fact that the use of IoT in the plastics industry will increase the volume of reusable products. IoT significantly improves production processes and product quality by enabling connectivity and communication between devices and systems. These changes include improving the efficiency of production lines, reducing raw material waste, increasing accuracy in quality control, and improving management processes. In general, IoT will greatly contribute to improving the performance and efficiency of reusable product production by creating connections between devices and the ability to collect and analyze data.

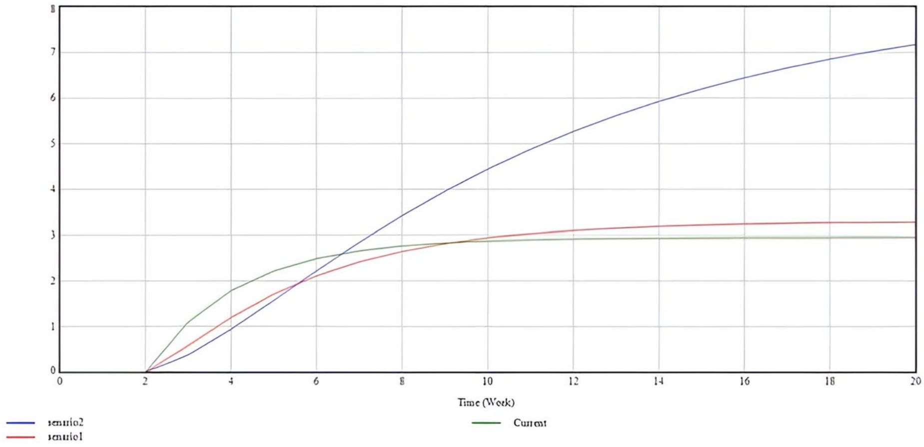

Fig. 8 Reusable Products

The amount of plastic waste in the agricultural industry is very important. The use of plastic in agriculture is used due to its light weight, flexibility and resistance to water and environmental conditions. However, the plastic waste produced from these activities causes environmental pollution and harm to animals and plants. Therefore, reducing the use of plastic and using renewable and reusable alternatives for packaging and agricultural products is very important. Also, using renewable materials to produce fertilizers and pesticides can help reduce plastic waste in the agricultural industry. Therefore, the importance of measures that lead to the reduction of plastic consumption and disposal in the agricultural industry is very significant. Figure 9 shows the current status of plastic waste used in the agricultural sector and different scenarios and states that its amount will increase over time.

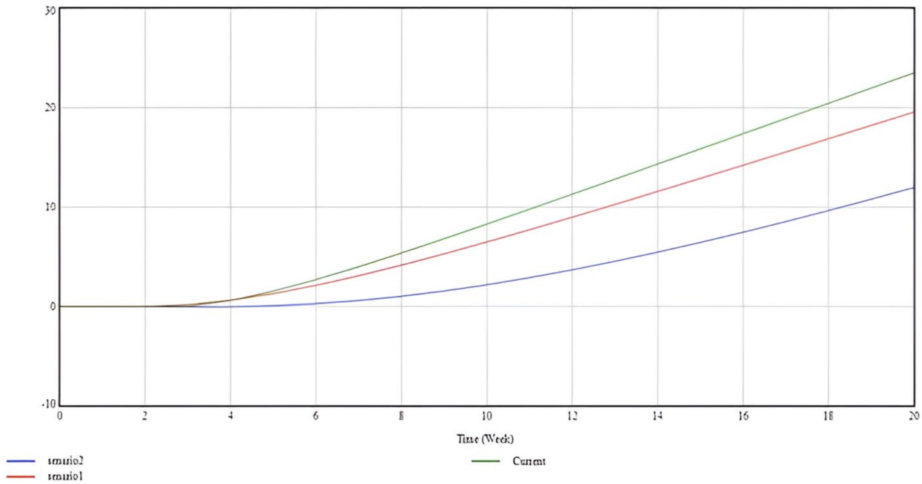

Fig. 9 Discarded Products

The use of modern technologies in scenarios 1 and 2 shows a reduction in waste. Digitalization can significantly reduce the amount of plastic waste produced from its operations by creating innovative and biodegradable plastic materials in the agricultural industry. This can have a positive impact on the environment and contribute to a more sustainable future for agriculture.

The products collected in the agricultural plastic supply chain can be used as part of the cultivation and harvesting process or for transporting agricultural products. They can also be used as part of the equipment needed by farmers to carry out their daily tasks on the farm. Since plastic is durable and easy to transport, its use in the agricultural plastic supply chain is very common. The use of plastic in the agricultural supply chain can also help improve the preservation and storage of agricultural products, as these materials can protect against moisture and various contaminants. In addition, the use of plastic in the packaging and transportation of agricultural products can help reduce waste and increase the shelf life of products. However, excessive use of plastic can lead to environmental pollution, so it is necessary to explore other methods to reduce the use of plastic and recycle it in the agricultural supply chain. Figure 10 shows the changing situation of collected products at a low level. In Scenario 1, the use of intelligent transportation systems will increase this variable. In Scenario 2, the Internet of Things will have a significant impact on increasing the important system variable.

Retailer backorders refer to customer orders that are not fulfilled or delivered by the retailer. This can be due to various reasons such as inventory shortages, logistical issues, or other complications that prevent the retailer from fulfilling the customer order. As can be seen in Fig. 11, this variable initially increases in all three cases and then decreases. In Scenario 1, this variable is reduced by using an intelligent transportation system. Adding IoT to the system improves supply chain performance and reduces this variable.

Manufacturer inventory refers to goods or products that a manufacturer has on hand and is ready to sell or distribute to customers. This inventory is typically held in the manufacturer's warehouse or production facility until it is needed for orders or shipments. In Scenario 2, the manufacturer's inventory is at a desirable level that allows customer orders to

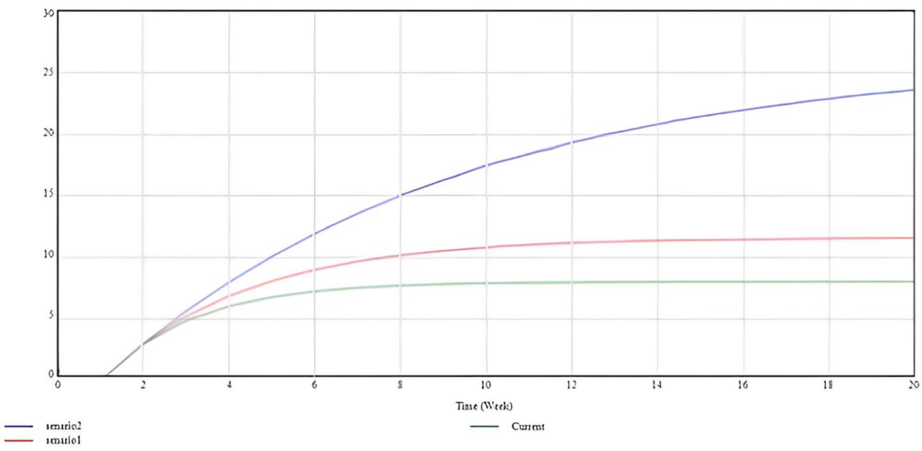

Fig. 10 Collected Products

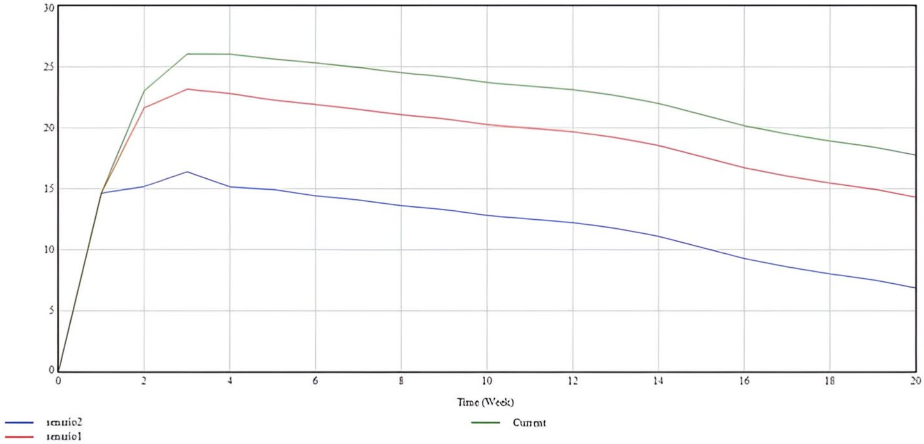

Fig. 11 Retailer’s Unfulfilled Orders

be fulfilled and associated costs to be reduced. In this case, too, the use of new technologies will improve performance. Figure 12 illustrates these behaviors.

As is clear from the scenario analysis results, intelligent transportation management and IoT technologies have a significant impact on the state variables in the plastic circular supply chain performance model.

Conclusion and Suggestions

In the last decade, due to the creation of environmental problems and disruption of the ecosystem cycle, the need to examine the performance of circular supply chain management has been considered. One of the attractive industries to study in this area is the plas-

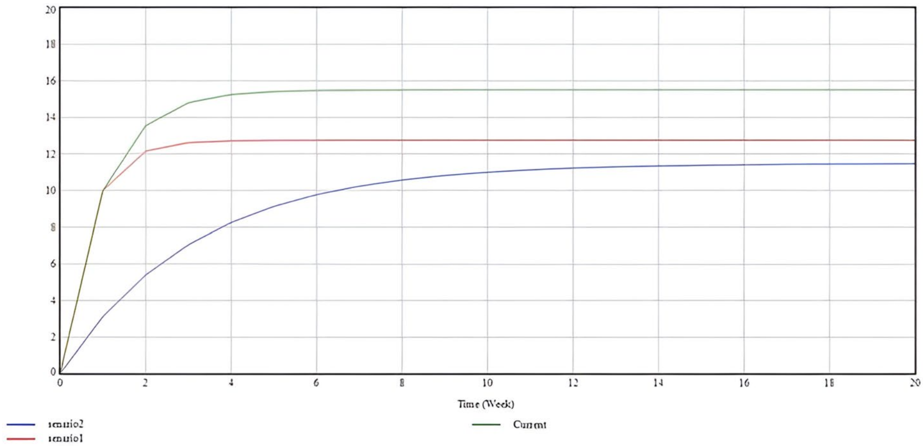

Fig. 12 Inventory in the Hands of the Producer

tics industry. In this study, a system dynamics model has been developed for the strategic restructuring and planning of the collection capacity of a product for recovery in the circular supply chain in the plastics industry. In circular supply chains, environmental concerns always impose constant pressure on the entire supply chain to formulate policies and enforce strict regulations.

The developed model of this study allows for a comprehensive description and analysis of system operations by considering capacity considerations, alternative environmental protection policies such as take-back commitments, and the effect of green image on product demand. System dynamics simulation can provide insights for developing efficient capacity planning policies in a dynamic manner. This model can be used to analyze different scenarios to identify efficient policies.

In order to answer questions related to the long-term performance of circular supply chains, variables from the production, distribution and recycling sectors of the overall supply chain can be used as performance metrics. Also, this model can be used not only for product recovery but also for material recycling systems. Therefore, it may be useful for policy makers/regulators and decision makers dealing with circular supply chain management issues.

In the case of the designed model, a very important issue is the impact of new technologies on the performance of circular supply chains. For this purpose, the impact of Internet of Things and transportation system management technologies on the model has been investigated. Transportation system management can contribute to efficiency in logistics and transportation. To strengthen this concept, this study showed that transportation system management has an impact on system state variables.

Thanks to IoT networks, transportation system management platforms simultaneously ensure logistical improvements by eliminating queues and barriers and support environmental compliance by providing options for reducing carbon dioxide emissions. Digitalization has had a major impact on the circular plastic supply chain, especially in the areas of raw material management, production, transportation, warehousing, recycling and distribution. On the one hand, digitalization has brought about significant improvements in the productivity and efficiency of the circular plastic supply chain. On the other hand, these changes will increase new challenges and problems in supply chain management that require new and innovative solutions. In this regard, the increased use of communication and information technologies has enabled better communication and coordination between supply chain members and has provided managers with more accurate and timely information. This will improve planning and forecasting of market needs, optimize inventories, and reduce warehousing and transportation costs. However, information security issues, sudden changes in technology, and the need to retrain employees are also challenges associated with the digitalization of the plastics supply chain.

In general, digitalization has multiple impacts on the plastics circular supply chain, and managers need to use new management methods to deal with these developments. In the future, with the advancement of artificial intelligence, Internet of Things, and e-commerce technologies, the impact of digitalization on the plastics circular supply chain is expected to increase significantly. This requires the use of analytical and predictive capabilities for managers to be able to face the changes and benefit from the new opportunities that these developments create. These findings reaffirm the core motivation of this study, which was to explore how digitalization can serve as a driver for addressing key sustainability challenges in the agricultural plastics supply chain, as outlined in the introduction.

According to the results, the use of components of new technologies such as intelligent transportation systems and the Internet of Things has improved the performance of all players in the plastics circular supply chain in the agricultural sector. Among them, we can mention the increase in collected goods and the reduction of discarded materials, which helps to fulfill the circular concept in the supply chain.

In order to examine the impact of digitalization on the performance of the circular supply chain of the plastics industry in the agricultural sector, several variables were analyzed under three scenarios. The first scenario is the current situation, that is, without the use of new technologies, the second scenario is the addition of a smart transportation system to the model, and in the final scenario, IoT technology was used to monitor and control the production and transportation processes of raw materials, finished products, and recycled materials. The results showed that transportation management systems optimize logistics networks. Supply chain performance improves with digitalization and the circular economy system improves with the implementation of IoT technology and the creation of sustainable practices. According to the findings of the study, it can be stated that smart transportation management technologies and IoT have a positive impact on the performance of the circular supply chain of plastics in the agricultural sector.

Research limitations in modeling the dynamics of the plastics industry system in the agricultural sector include the challenges that the researcher faced when trying to study and understand the complex interactions and processes in this particular industry. These limitations include data availability, model accuracy, lack of comprehensive understanding of industry dynamics, and other practical or theoretical limitations that may have affected the research results. Also, the unavailability of the exact amount of digitalization variables was very important in this research, which was considered approximate because this research was innovative and its amount was not reported in the literature.

Technologies can be a factor in sustainable development, but their role in circular supply chain management has not been well researched. There is a lot of room for exploration, analysis of big data for circular supply chain management. In this research, the impact of the Internet of Things and intelligent transportation system as components of digitalization on supply chain management was investigated. It is proposed to analyze the impact of block chain, as well as 3D printing, as another promising technology, to be an important driving force for realizing high-efficiency and low-cost customized manufacturing.

Researchers can also examine the circular economy issues arising from the production of a variety of products and the resulting short life cycles of customized products. From a practical perspective, to maximize their achievements, companies can combine transportation system management and the Internet of Things with other tools such as 3D printers and machine learning. These two technologies can work by strengthening the results related to circular supply chains, business performance and sustainable practices, because on the one hand, companies can train systems to make positive and green decisions through machine learning, while on the other hand, 3D printers can extend the life cycle of products.

Although complete replacement of plastics is not currently possible without increasing the overall environmental impact and compromising food security, alternatives with lower environmental impact should be used and supported within a clear socio-economic framework. Better monitoring and reporting, technical innovations, education, and social and economic incentives are essential to promote a more sustainable use of plastics in agriculture. In addition, we can mention such things as the creation of a smart supply chain management system capable of collecting, analyzing data related to the production, distribution and sale of plastic products in the agricultural sector. The creation of an artificial intelligence system to predict market needs and adjust production and distribution to optimize inventory and reduce material waste. The promotion of circular supply chain management information systems to increase transparency and confidence about the resources used and the operating conditions of suppliers.

The results of this study align with Kazancoglu et al. [47] who demonstrated the efficiency gains of reverse logistics in food supply chains. However, this research extends those findings by illustrating that integrating IoT and smart transportation systems not only improves reverse logistics efficiency but also significantly reduces lead time and operational costs in a circular economy context. This dual impact on operational and environmental performance was not previously quantified in the agri-food supply chain literature. Moreover, unlike Kumar et al. [45], who focused on sustainability indices using MCDM, this study provides a dynamic operational model capable of testing various digitalization scenarios over time.

Managerial and Practical Implications

The findings of this study offer practical guidance for managers and policymakers in the agricultural sector. By demonstrating the operational and environmental benefits of IoT-based tracking systems and smart transportation integration within circular supply chains, the model enables informed decision-making regarding digitalization investments. Sensor-assisted data collection can be used to accurately measure soil moisture, temperature, and other environmental parameters, as well as to regulate the use of greenhouse plastics and plastic mulch. Data management systems can be used to monitor plastic waste and implement more effective recycling programs. This can be mitigated by promoting the use of biodegradable plastics and developing alternative technologies to reduce dependence on traditional plastics. By using modeling and simulation to predict the need for plastics at different stages of cultivation and harvesting and reducing waste due to inaccurate estimates, daily performance can be increased. Digital agriculture contributes to environmental sustainability by reducing waste and optimizing consumption, and reduces the negative impacts of plastics on ecosystems. Sensors and digital data can also be used to precisely adjust irrigation and reduce water and plastic consumption associated with irrigation. Digital data can be used to accurately forecast demand and reduce waste from excessive packaging. With the smart use of digital technologies, agriculture can move towards a more sustainable and environmentally friendly approach. Although the model was developed for agricultural plastics, its structure and logic can be adapted to other industries with similar closed-loop supply chain characteristics, such as electronics or automotive parts. The results are particularly valid in contexts where digital infrastructure and reverse logistics systems are already operational or can be feasibly established.

In this study, by designing a system dynamics model, the impact of digitalization on the performance of the circular supply chain of the plastics industry, various variables of the production, distribution and recycling sectors of the supply chain were analyzed during the simulation period, so that companies can determine scenarios for their specific transition to circular supply chain management in case studies. The innovation of this research included the design and implementation of a circular supply chain model with a system dynamics approach in the agricultural plastics industry and the addition of variables related to digitalization to it.

Author Contributions Keshavarz kohjerdie: sample collection, data curation.
Ghorbanpour: conceptualization, methodology, formal analysis, writing –original draft and editing, preparation, project administration, software.
Jamali: conceptualization, methodology, resources, preparation, review and editing.
All authors have read and agreed to the published version of the manuscript.

Funding Not applicable.

Data Availability Not applicable.

Declarations

Ethical Approval Not applicable.

Consent To Participate All authors consent to participate in the works of manuscript.

Consent To Publish All authors consent for publication.

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

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