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ORIGINAL RESEARCH

Diffusing sustainable supply chains: a hybrid evolutionary game theory and system dynamics approach

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Abstract

This study develops a comprehensive policy-making model to diffuse sustainable supply chain management (SSCM) across pharmaceutical supply chains (PSCs), addressing triple bottom line (TBL) concerns—people, planet, and profit—while considering stakeholder dynamics interactions and unexpected events like global pandemics. Initially, the pharma industry's most essential TBL criteria are extracted by systematically reviewing the extant literature. Next, two different types of evolutionary game theory (EGT) (i.e., pairwise contest game (PCG) and tripartite evolutionary game (TEG)) are innovatively integrated to describe the stakeholders' interactions, providing a theoretical basis for assessing strategy stability and sustainable practice diffusion across multi-tiered and multi-echelon PSCs under regulators' interventions. Then, a system dynamics (SD) model is developed based on the EGT models to simulate the targeted policy-making system based on Iran's PSC as a case study. Key findings reveal that COVID-19 health protocols and lockdowns increased work avoidance among Regulatory Enterprises (REs), but long-term adherence to sustainable policies by distributors (Ds) and retailers (Rs) is projected by 2228. Five policies—imposing fines, segregation and public disclosure, increased punishments and incentives, rewards for sustainable practices, and subsidies for sustainable purchases—are recommended to accelerate sustainable adoption by 2056, eliminate RE work avoidance, and achieve significant outcomes: a monthly reduction of over 2,000 expired products, a decrease of around 1,000 TCO2e (Tons of Carbon Dioxide Equivalent) in upstream CO_2 emissions, an increase of over 600 TCO2e in CO_2 neutralisation, and over 100 new monthly job vacancies. This highlights the model's potential to diffuse economic, environmental, and social sustainability in PSCs post-COVID-19 under regulations.

Keywords Sustainable supply chain · Diffusion · Triple bottom line · Evolutionary game theory · System dynamics

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1 Introduction

Sustainable supply chain management (SSCM) integrates the triple bottom line (TBL) pillars to manage supply chain (SC) processes, information, resource flows, and partner interactions. This approach ensures that stakeholders' needs are met while enhancing the productivity, profitability, and resilience of SCs (Ahi & Searcy, 2013). Despite a yearly surge in SSCM research, widespread concerns about global environmental degradation, social inequities, and economic instability showcase the challenges in effectively diffusing sustainable practices across diverse SCs in different industries (Pimenta et al., 2021). As a case in point, the United Nations' Sustainable Development Goals targeted the pharmaceutical industry to promote its sustainability, elevate its merits and lessen its detrimental impacts (Viegas et al., 2019).

Generally, pharmaceutical supply chains (PSC) are praised for improving profitability, health, and life expectancy. For instance, it directly employed 865,000 European workers in 2022 (EFPIA, 2023). Moreover, the global pharmaceutical (prescription) market approximated €1,222,921 million at ex-factory prices in 2022 (EFPIA, 2023). Its revenues are over US$825 billion, with an annual average growth of 4–6% (Bravo & Carvalho, 2015). However, critics point out its high energy consumption, toxic waste and pollution, and low social responsibility toward staff satisfaction and consumers' health (Goodarzian et al., 2021; Halim et al., 2019). Still worse, this has been exacerbated since the COVID-19 pandemic emergence. For example, PSC emits about 52 megatons of CO2e yearly (Belkhir & Elmeligi, 2019). By 2025, it is obliged to diminish the severity of its emissions (by 59% from 2015 levels) to reach the goals of the Paris Agreement (Belkhir & Elmeligi, 2019). Not surprisingly, functionally diffusing SSCM across PSC through systems thinking is a unique contribution to addressing all these concerns.

Since 2012, there has been a growing focus on SSCM diffusion in conjunction with institutional theory as a solution to spreading sustainability initiatives among SC partners from one tier and/or echelon (i.e., suppliers, manufacturers, Ds, and Rs) to the next, under various pressures from both market and non-market stakeholders (Luthra et al., 2020). Irrespective of several relevant recent research (e.g., Luthra et al., 2020; Meqdadi et al., 2019; Pimenta et al., 2021), there has been a significant oversight in developing a realistic model for SSCM diffusion. To compensate for this drawback, a comprehensive policy-making system is imperative in which SC echelons and tiers, stakeholders' dynamic interactions, and all TBL pillars are simultaneously considered (Rebs et al., 2019). Moreover, the dynamic evolution of SSCM diffusion should be represented realistically. With limited rationality, each SC member must imagine who can learn by comparing their payoff with counterparts and imitation, gaining knowledge and adjusting their strategies to reach the optimal payoff (Meqdadi et al., 2019). Cleverly, all the above principles can be likened to the dynamic logic of evolutionary game theory (EGT) complemented by the system dynamics (SD) approach (Qiu et al., 2021). Fortunately, the SD-based EGT model is popularly suitable enough to propagate sustainability initiatives effectively. For instance, Tian et al. (2014) is the most relevant study that combined pairwise contest game (PCG) and SD to diffuse green SCM across manufacturers in China's automobile industry.

Nonetheless, there are still various areas of development to enhance such a model's compatibility with reality. Purposefully, this paper contributed to developing instance models from different perspectives to bridge the above and following research gaps. Foremost, diffusing SSCM across PSC during a health crisis has not been successful, particularly in low-income emerging economies like Iran, which have shown low-level performance in achieving United Nations goals (Liu & Li, 2023; Tian et al., 2014). As the second neglected area, separating sustainable development into three main pillars, identifying the most paramount criteria of each class, and quantitatively measuring such indicators is another research requirement to achieve that worldwide ambition (Goodarzian et al., 2024). This issue is more highlighted in the pharma industry because the PSC sustainable TBL matrix has been widely investigated since 2015 (Janatyan et al., 2021). Although economic and environmental aspects have been mainly evaluated (Shamsuzzoha et al., 2020), there is a dearth of investigations on social responsibility and all TBL metrics (Roshan et al., 2019). Thirdly, current complex SCs are not constrained to one echelon and tier with one product in the sole period. Hence, modelling a multi-echelon-tier-product-and period is another research demand, especially in the pharma industry, where the reciprocal relationship between multi-stakeholder interactions and TBL matrices has not yet been addressed (Wang et al., 2021a, 2021b). To our knowledge, innovatively integrating two types of EGT models (PCG and tripartite evolutionary game (TEG)) with SD is a novel trick to simulate sustainability initiatives propagation according to a real-world complex and dynamic competitive market.

By originatively combining the PCG and TEG models, we introduce a new theoretical framework that enhances the analysis of interactions within and across stakeholder groups in PSCs. The PCG model focuses on competitive dynamics between two types within a single population (Yu et al., 2022). In contrast, the TEG model extends this to explore competitive behaviours among three distinct populations (Pan et al., 2024). This integrated approach thoroughly examines the intricate relationships between PSCs and governmental bodies. Additionally, it offers a solid theoretical foundation for concurrently evaluating strategy stability and the propagation of sustainable practices within multi-tiered and across multi-echelon PSC structures. Additionally, SD captures the feedback-driven nature of stakeholder interactions over time, revealing how short-term decisions impact long-term outcomes. It also enables simulations of scenarios like external shocks (e.g., pandemics) and policy interventions on sustainable practices. Ultimately, SD complements EGT models by translating strategic interactions into measurable results (Tian et al., 2014).

Ergo, two main objectives are derived from this research. **RO$_1$**. To innovatively develop a dynamic and general hybrid model for diffusing economic, environmental, and social sustainability across multi-echelon and tier PSCs with multi-product in a multi-period, covering the advent, outbreak times, and aftermath of the global pandemic, under the pressure of market and non-market stakeholders (e.g., government, customers, competitors). **RO$_2$**. To create an original policy-making system through scenario analysis for the Iranian pharma industry to journey from unideal to ideal PSC sustainability diffusion in a specific time framework.

Subsequently, four research questions are defined to fulfil such aims. **RQ$_1$ (Based on SLR)**. (i) What are the most paramount PSC sustainability criteria for each economic, ecological, and social pillar? (ii) Which echelons of PSC and stakeholders (market and non-market) are the most critical to study? (iii) What is the main development area for innovatively enhancing the extant SD-based EGT models to be more compatible with the real-world competition market? **RQ$_2$**. What are the replicator dynamics equations and payoff functions of combined evolutionary games (PCG and TEG)? **RQ$_3$**. How does a dynamic model systematically illustrate the combination of PCG and TEG based on principles of the demand–supply market influenced by the global pandemic? **RQ$_4$**. What are the key variables' of Iranian PSC's current situation resulting from the initial simulation, and which scenarios lead to an ideal situation?

To this end, Sect. 2 reviews the literature on sustainable PSC and integrated EGT-SD approaches. Based on the EGT models (PCG and TEG) and the demand–supply market influenced by the global pandemic, Sect. 3 develops the SD model. Section 4 reports the initial simulation results of the case study. Section 5is assigned to scenario analysis and implications. Eventually, this paper ends with the ultimate remarks, including the conclusion, limitations, and future recommendations in Sect. 6.

2 Literature review

PSC composes an integrated network of suppliers, manufacturers, Ds, and Rs (pharmacies and hospitals) to produce and deliver drug products to consumers. Sustainable PSC management attempts to reach the mentioned goal via economically viable, non-polluting, and non-wasteful activities, saving limited material and resources to protect the environment and keep it safe and sound for society (Halim et al., 2019). Sustainable PSC has been significantly considered by researchers, pharmaceutical companies, policymakers, and consumers (Janatyan et al., 2021; Low et al., 2016; Milanesi et al., 2020). The first systematic literature review (SLR) has been conducted in the context of sustainable PSCs, illustrating the existing research gaps and trends.

To this end, Scientific Procedures and Rationales for Systematic Literature Reviews (SPAR-4-SLR), including eight criteria, were employed (Paul et al., 2021), including (i) input, (ii) scope of the research, (iii) keywords, (iv) period, (v) document type, (vi) language, (vii) the type and quality of sources, and (viii) search mechanisms. Specifically, we focused on sustainability or TBL measures for sustainable PSCs (research input and scope). The review underlined English-language research articles, indexed in Scopus and Web of Science, published by Springer, ScienceDirect, Emerald, Tylor & Francis, and Wiley. Additionally, journals deemed acceptable by the Australian Business Deans Council (ABDC) were examined for source quality due to their recognised reliability and widespread acceptance (Paul et al., 2021). Accordingly, articles with relevant titles, abstracts, and keywords covering (*"sustainability" OR "sustainable" OR "sustainable development" OR "sustainability measures") AND ("pharmaceutical supply chain" OR "pharma supply chain"*) were targeted, initially resulting in 150 works. Applying the period filter, the 140 remaining sources were selected and published between 2016 and July 2024. Next, 33 duplicated items were removed. The other five filters, along with subject areas, including Business, Management, and Accounting, and topics involving sustainable development, SCM, SSCM, closed-loop SCM, and green SCM, were then applied to 107 remaining records, excluding 68 irrelevant items. After thoroughly reading the titles and abstracts of the remaining 39 relevant studies, four papers were deemed irrelevant and excluded. As a result, Table 1 summarises the results of reviewing 35 selected articles in sustainable PSCs from 2016–2024.

With the second column of Table 1 in mind, research gaps in sustainable PSC can be identified from the following perspective. Foremost, the 35 distinguished articles can be divided into four main categories based on their contribution: (i) sustainable PSC network design, (ii) PSC sustainability measures optimisation, (iii) sustainable partnerships selection, and

Table 1 Sustainable PSCs research

References	Contribution	PSC echelon	Sustainability measures			Type of approach							
			Economic	Environmental	Social	Systematic literature review	Data mining	Statistical analysis	Multi-criteria decision making	Mathematical modeling	Classical game theory	Evolutionary game theory	System dynamics
Weraikat et al. (2016a)	Reverse PSC network design	M, R, CD, G	Profit, market demand	–	–					✓			
Low et al. (2016)	Environmentally sustainable PSC network design	SUP, M	Cost, lead time	GHG emission	–				✓				
Weraikat et al. (2016b)	Sustainable reverse PSC network design	M, CD	Profit, market demand	–	–					✓			
Zahiri et al. (2017)	Sustainable, resilient PSC network design	M, D, CD	Cost, regional economic development	GHG emission	Job creation					✓			
Chaturvedi et al. (2017)	Review of sustainable development of PSC	–	–	–	–	✓							
Campos et al. (2017)	Review of sustainable PSC	–	–	–	–	✓							
Zhu et al. (2018)	Integrate sustainable and lean SC to facilitate a product deletion decision	–	Cost	GHG emission	–				✓				

Table 1 (continued)

References	Contribution	PSC echelon	Sustainability measures			Type of approach							
			Economic	Environmental	Social	Systematic literature review	Data mining	Statistical analysis	Multi-criteria decision making	Mathematical modeling	Classical game theory	Evolutionary game theory	System dynamics
Tsolakis and Srai (2018)	Map dynamic green PSC	–	Quality	Volumes of waste and recovery	–								✓
Zahiri et al. (2018)	Sustainable PSC network design	PM, SM, D, CD	Cost, market demand	–	–					✓			
Nematollahi et al. (2018)	Social sustainable PSC network design	D, R	Profit, service level, market demand	–	–					✓			
Roshan et al. (2019)	Sustainable PSC network design	PM, SUP	Cost, regional economic development	–	Employment or recruiting					✓			
Weraikat et al. (2019)	Sustainable PSC network design	M, CD (H), G	Cost, market demand	Expired medication quantities	–					✓			
Kumar et al. (2019)	Prioritise potential risks to initiate a green PSC	–	–	–	–				✓				

Table 1 (continued)

References	Contribution	PSC echelon	Sustainability measures			Type of approach							
			Economic	Environmental	Social	Systematic literature review	Data mining	Statistical analysis	Multi-criteria decision making	Mathematical modeling	Classical game theory	Evolutionary game theory	System dynamics
Halim et al. (2019)	Selection of sustainable suppliers and manufacturers to optimise the PSC network	SUP, M	Cost, quality, delivery time, market demand	GHG emission	Regulatory compliance, technical competency				✓	✓			
Viegas et al. (2019)	Review of reverse flow within the PSC network	–	–	–	–	✓							
Zandkarimkhani et al. (2020)	PSC network design	SUP, D, CD	Cost, market demand	–	–					✓			

Table 1 (continued)

References	Contribution	PSC echelon	Sustainability measures			Type of approach							
			Economic	Environmental	Social	Systematic literature review	Data mining	Statistical analysis	Multi-criteria decision making	Mathematical modeling	Classical game theory	Evolutionary game theory	System dynamics
Pesqueira et al. (2020)	Challenge reduction of social sustainability of PSC	–	–	–	Employment or recruiting, retaining, discovering professional skills		✓						
Milanesi et al. (2020)	Review of sustainable PSC	–	–	–	–	✓							
Shamsuzzoha et al. (2020)	Optimisation of the logistics system	SUP	Profit, cost, market demand	GHG emission	–			✓					
Liu et al. (2020)	Sustainable reverse PSC network design	M, CD, G	Profit, market demand	–	–					✓			

Table 1 (continued)

References	Contribution	PSC echelon	Sustainability measures			Type of approach							
			Economic	Environmental	Social	Systematic literature review	Data mining	Statistical analysis	Multi-criteria decision making	Mathematical modeling	Classical game theory	Evolutionary game theory	System dynamics
Shokouhyar et al. (2020)	Impact evaluation of big data on sustainable PSC	–	–	–	–		✓						
Moosivand et al. (2021)	Sustainable management of medicine shortages	–	–	–	–				✓				
Goodarzian et al. (2021)	Sustainable PSC network design in the COVID-19 outbreak era	L, PC, D, H	Cost, regional economic development	GHG emission	Job creation					✓			✓
Sazvar et al. (2021)	Closed-loop PSC network design	M, D, PH, DC, RM	Profit, market demand	GHG emission	Job Opportunity					✓	✓		
Janatyan et al. (2021)	Sustainable medicine distribution network design	D, CD	Cost, quality, market demand	GHG emission	Job creation					✓			
Ahmad et al. (2022)	Sustainable PSC network design	SUP, M, D, CD, DC	Profit, cost, market demand	Carbon emissions	customers' satisfaction				✓	✓			

Table 1 (continued)

References	Contribution	PSC echelon	Sustainability measures			Type of approach							
			Economic	Environmental	Social	Systematic literature review	Data mining	Statistical analysis	Multi-criteria decision making	Mathematical modeling	Classical game theory	Evolutionary game theory	System dynamics
Sazvar et al. (2022)	Sustainable Closed-loop PSC network design	M, D, PH, DC, SM	Profit, cost, market demand	Expired medication quantities, carbon emission	Job opportunities					✓	✓		
Malleeswaran and Uthayakumar (2022)	Sustainable PSC network design	SUP, R	Profit, cost, market demand	Expired medication quantities, GHG emissions, energy consumption	Safety					✓			
Romdhani et al. (2022)	Sustainable PSC inventory design	D, R (H)	Cost, lead time, market demand	Waste	–					✓			
Hosseini-Motlagh et al. (2022)	Investigating the role of government and social awareness in minimising the number of unwanted medications	M, D	Profit, cost, market demand	Expired medication quantities	Social image					✓			
Rekabi et al. (2023)	Sustainable PSC network design	M, D	Travel time and cost, resource allocation, market demand	–	–					✓			

Table 1 (continued)

References	Contribution	PSC echelon	Sustainability measures			Type of approach							
			Economic	Environmental	Social	Systematic literature review	Data mining	Statistical analysis	Multi-criteria decision making	Mathematical modeling	Classical game theory	Evolutionary game theory	System dynamics
Lotfi et al. (2023)	Sustainable Closed-loop PSC network design	M	Profit, cost, market demand	Waste, recycle	Customer satisfaction				✓	✓			
Bade et al. (2024)	assess sustainability maturity and impacts of sustainability measure implementation on PSC security	G, pharma industry	–	Energy consumption, waste, GHG emission	Staff health, training,			✓					
Goodarzian et al. (2024)	Sustainable PSC network design	D, R (PH)	–	Carbon emission	–					✓			
Shekoohi Tolgari and Zarrinpoor (2024)	Sustainable reverse PSC network design	D, R	Cost, national self-sufficiency, market demand	GHG emissions, water use, energy consumption, waste,	Job opportunities, job satisfaction				✓	✓			

Table 1 (continued)

References	Contribution	PSC echelon	Sustainability measures			Type of approach							
			Economic	Environmental	Social	Systematic literature review	Data mining	Statistical analysis	Multi-criteria decision making	Mathematical modeling	Classical game theory	Evolutionary game theory	System dynamics
Current study	Diffusing sustainability across PSC under the pressure of both market and non-market stakeholders and impacts of a global pandemic like COVID-19	D, R (PH), CD, G	cost, profit, market demand, payoff	CO_2emission and neutralisation of expired medication quantities	Job creation	✓						✓	✓

References	Contribution	PSC echelon	Type of uncertainty	Solution method			Type of validation		
				Exact	Heuristic/ meta-heuristic algorithm	Simulation	Case study	Design of experiment	Sensitivity analyses
Weraikat et al. (2016a)	Reverse PSC network design	M, R, CD, G	–		✓		✓		
Low et al. (2016)	Environmentally sustainable PSC network design	SUP, M	–	✓			✓		
Weraikat et al. (2016b)	Sustainable reverse PSC network design	M, CD	–	✓			✓	✓	
Zahiri et al. (2017)	Sustainable, resilient PSC network design	M, D, CD	Hybrid method		✓		✓		
Chaturvedi et al. (2017)	Review of sustainable development of PSC	–	–	–	–	–	–	–	–
Campos et al. (2017)	Review of sustainable PSC	–	–	–	–	–	–	–	–

Table 1 (continued)

References	Contribution	PSC echelon	Type of uncertainty	Solution method			Type of validation		
				Exact	Heuristic/ meta-heuristic algorithm	Simulation	Case study	Design of experiment	Sensitivity analyses
Zhu et al. (2018)	Integrate sustainable and lean SC to facilitate a product deletion decision	–	–	✓			✓		
Tsolakis and Srai (2018)	Map dynamic green PSC	–	–			✓	✓		
Zahiri et al. (2018)	Sustainable PSC network design	PM, SM, D, CD	Robust/ possibilistic robust	✓			✓	✓	✓
Nematollahi et al. (2018)	Social sustainable PSC network design	D, R	Stochastic	✓				✓	
Roshan et al. (2019)	Sustainable PSC network design	PM, SUP	Fuzzy		✓		✓		
Weraikat et al. (2019)	Sustainable PSC network design	M, CD (H), G	–	✓		✓	✓		
Kumar et al. (2019)	Prioritise potential risks to initiate a green PSC	–	Fuzzy	✓			✓		
Halim et al. (2019)	Selection of sustainable suppliers and manufacturers to optimise the PSC network	SUP, M	–	✓			✓		
Viegas et al. (2019)	Review of reverse flow within the PSC network	–	–	–	–	–	–	–	–
Zandkarimkhani et al. (2020)	PSC network design	SUP, D, CD	Fuzzy		✓		✓		✓
Pesqueira et al. (2020)	Challenge reduction of social sustainability of PSC	–	–	–	–	–	✓		
Milanesi et al. (2020)	Review of sustainable PSC	–	–	–	–	–	–	–	–
Shamsuzzoha et al. (2020)	Optimisation of the logistics system	SUP	–			✓	✓		
Liu et al. (2020)	Sustainable reverse PSC network design	M, CD, G	–		✓		✓		✓
Shokouhyar et al. (2020)	Impact evaluation of big data on sustainable PSC	–	–	–	–	–	✓		
Moosivand et al. (2021)	Sustainable management of medicine shortages	–	–	✓			✓		

Table 1 (continued)

References	Contribution	PSC echelon	Type of uncertainty	Solution method			Type of validation		
				Exact	Heuristic/meta-heuristic algorithm	Simulation	Case study	Design of experiment	Sensitivity analyses
Goodarzian et al. (2021)	Sustainable PSC network design in the COVID-19 outbreak era	L, PC, D, H	–		✓	✓	✓		✓
Sazvar et al. (2021)	Closed-loop PSC network design	M, D, PH, DC, RM	Hybrid method		✓		✓		✓
Janatyan et al. (2021)	Sustainable medicine distribution network design	D, CD	Robust/possibilistic robust		✓		✓		
Ahmad et al. (2022)	Sustainable PSC network design	SUP, M, D, CD, DC	Fuzzy		✓		✓		
Sazvar et al. (2022)	Sustainable Closed-loop PSC network design	M, D, PH, DC, SM	–		✓		✓		
Malleeswaran and Uthayakumar (2022)	Sustainable PSC network design	SUP, R	–	✓					✓
Romdhani et al. (2022)	Sustainable PSC inventory design	D, R (H)	–	✓					✓
Hosseini-Motlagh et al. (2022)	Investigating the role of government and social awareness in minimising the number of unwanted medications	M, D	–	✓			✓		✓
Rekabi et al. (2023)	Sustainable PSC network design	M, D	–	✓					✓
Lotfi et al. (2023)	Sustainable Closed-loop PSC network design	M	–	✓			✓		
Bade et al. (2024)	assess sustainability maturity and impacts of sustainability measure implementation on PSC security	G, pharma industry	–	✓			✓		
Goodarzian et al. (2024)	Sustainable PSC network design	D, R (PH)	–		✓		✓		✓

Table 1 (continued)

References	Contribution	PSC echelon	Type of uncertainty	Solution method			Type of validation		
				Exact	Heuristic/ meta-heuristic algorithm	Simulation	Case study	Design of experiment	Sensitivity analyses
Shekoohi Tolgari and Zarrinpoor (2024)	Sustainable reverse PSC network design	D, R	Fuzzy, Robust		✓		✓		
Current study	Diffusing sustainability across PSC under the pressure of both market and non-market stakeholders and impacts of a global pandemic like COVID-19	D, R (PH), CD, G	–			✓	✓		✓

PSC echelon: SUP: Supplier, **M**: Manufacturer, **PM**: Primary manufacturer, **SM**: Secondary manufacturer, **D**: Distributor, **R**: Retailer, **CD**: customer demand, **H**: Hospital, **PH**: Pharmacy, **L**: Laboratory, **DC**: Disposal centre, **G**: Government

(iv) PSC sustainability risk analysis. Accordingly, recent scholars have not targeted diffusing sustainability across PSCs, which is the main contribution of this study. Secondly, despite wide surveys on different managerial issues on sustainable PSC (see Table 1), investigating sustainable PSC network modelling still needs to adequately consider a holistic framework suggested by Rebs et al. (2019). In this context, a systems thinking approach is crucial for simultaneously considering PSC echelons and tiers, dynamic interactions among market and non-market stakeholders, and all TBL pillars. Nonetheless, no article has addressed stakeholders' conflicting interests and interactions, the PSC echelons and the TBL matrices.

Besides, although most scholars emphasised a multi-echelon PSC, they mainly restricted each echelon into one-tier. However, current PSCs are too complex to be modelled by such a simple configuration. Imagining a population of each echelon is vital, though neglected, to realistically modelling complex PSC members' interactions. Moreover, recent papers have studied pairwise and triplex levels of upstream (i.e., suppliers), midstream (i.e., manufacturers), and downstream (i.e., Ds, Rs, and customer demand). To our best knowledge, scholars have yet to study two downstream echelons of PSC, Ds and Rs, by considering their complicated dynamic interactions as well as the conflicting interests of other stakeholders. For instance, REs, governments, consumer demand, and the effects of unexpected natural crises (e.g., the impact of the COVID-19 pandemic on PSC sustainability management) have yet to be investigated (see Table 1, column 3).

Interestingly, all attempts have been devoted to optimising sustainability measures, regardless of 20% of studies that did not distinguish sustainability into any TBL measures. At a glimpse, the economic pillar has been mostly (71.4%) indicated, followed by environmental (54.3%) and social effects (40%), respectively. Specifically, 25.7% studied one pillar [i.e., economic (78%), environmental (11%), and social (11%)], 22.8% focused on two pillars [i.e., economic and environmental (75%), economic (or environmental) and social (25%)], and 31.5% emphasised the entire TBL matrices. Not surprisingly, being in the third group, a trend since 2021, is comprehensive enough to be conducted (see Table 1, column 4).

Moreover, the identified PSCs' TBL measures for each pillar with their frequency are as follows: (i) Economic pillar includes market demand (76%), cost (68%), profit (44%), quality (12%), regional economic development (12%), lead time (8%), travel time (4%), delivery time (4%), resource allocation (4%), national self-sufficiency (4%), and service level (4%). (ii) Environmental pillar contains GHG (or carbon) emissions (63.1%), unwanted materials including waste and expired products (47.3%), energy consumption (15.8%), recycling (10.5%), and water used (5.3%). (iii) Social pillar covers job opportunities or creation (57.1%), consumers' satisfaction (14.3%), staff training (14.3%), job satisfaction (7.1%), safety (7.1%) and health (7.1%). Therefore, cost, profit, payoff, market demand, carbon emission and neutralisation, expired medication quantities, and job creation are the most paramount and frequent TBL measures of PSCs to work on in this study (see Table 1, column 4).

Regarding the applied methodologies, 80% of the reviewed studies applied a single method [e.g., mathematical modelling (53.6%), multi-criteria decision making (14.3%), SLR (14.3%), data mining (7.1%), statistical analyses (7.1%), system dynamics (3.5%)]. Since 2019, using hybrid methods has become more popular among 20% of scholars [e.g., mathematical modelling and multi-criteria decision-making (57.1%), mathematical modelling and classical game theory (28.5%), and mathematical modelling and system dynamics

(14.3%)]. As a neglected area, a qualitative and quantitative mixed method has not yet been employed (see Table 1, column 5). Moreover, 42.8% and 34.3% of the considered studies employed exact and heuristic or meta-heuristic algorithms in solving their developed models, respectively. Unfortunately, simulation has been hardly used (11.4%) (see Table 1, column 7). Nonetheless, it is the best computer-based solution approach to running and predicting a complex PSC model. Fortunately, employing case studies and sensitivity analyses is a trend to check model validity (see Table 1, column 8).

Tracing the abovementioned gaps and trends, a new qualitative and quantitative mixed method with a simulation solution approach, and two popular validation methods)case study and sensitivity analyses(should be innovatively selected in this research, acquiring three necessities of our main stated contribution: (i) the dynamic evolution of SSCM diffusion under various pressures from both market (consumers and PSCs' members) and non-market stakeholders (government and REs) (Pimenta et al., 2021), (ii) systems thinking in modelling sustainable PSCs (Rebs et al., 2019), (iii) macro level simulation and prediction in developing high-level comprehensive policies (Rebs et al., 2019). Therefore, SLR, EGT, and SD integration have been appropriately applied. The first SLR was recently implemented to address the first two parts of research question $\mathbf{RQ_1}$. Then, the dynamic logic of EGT complemented by the SD approach has been utilised to recognise all three obligations in dynamically diffusing sustainable practices among PSCs' members, considering the impacts of a global pandemic like COVID-19.

SSCM diffusion involves dynamic and systematic planning, implementation, control, and action (the Deming cycle) (Meqdadi et al., 2019). This process considers the overall and individual evolution of each SC member. Realistically, each member has bounded rationality, and they can learn from others by imitation, receiving feedback, gaining sufficient knowledge to choose or change their strategies, and thus driving improvement (Pimenta et al., 2021). Over time, this process repeats until an optimal payoff is achieved, leading to population evolution; thus, sustainability diffusion across PSC inherently follows the logic of dynamic EGT (Tian et al., 2014). The EGT model, widely used for solving SSCM issues, faces criticism for not fully capturing the real dynamics of game processes (Chen et al., 2020). To address this, scholars have integrated SD as a complementary tool for modelling the nonlinear behaviours abstracted from the EGT model (Qiu et al., 2021). SD effectively handles high complexity and uncertainty in SSCM, providing decision-makers with a macro-level policy-making environment (Rebs et al., 2019). However, SD alone is incomplete and requires another quantitative approach, such as the EGT model, especially in capturing complex dynamic interactions among SC's stakeholders (Rebs et al., 2019). This was generally solved by visually stimulating the embodied game scenarios regarding a nonlinear feature of stakeholder interactions.

Hence, the second SLR has been conducted, contributing to the development areas of the SD-based EGT models, particularly in diffusing SSCM across PSCs' participants (the last part of $\mathbf{RQ_1}$). A similar approach and protocol of SPAR-4-SLR has been applied (Paul et al., 2021). We focused on combining the EGT and SD approaches employed in the SSCM context (research input and scope). Accordingly, articles with titles, abstracts, and keywords, including ("evolutionary game theory") AND ("system dynamics",) were targeted, initially yielding 181 works (material acquisition). Applying the period filter, the 171 remaining sources were selected and published between 2014 and 30 June 2024 (search period). Secondly, 49 duplicated items were removed. The rest of the filters [e.g., Subject area: Business, Management, and Accounting, Document type and language: English article, Topics: diffusion, sustainable development, SCM, SSCM, closed-loop SCM, green SCM, Publisher: Springer, ScienceDirect, Emerald, Tylor & Francis, and Wiley, Source type and quality: ABDC journal] were then applied to 122 remaining records, resulting in the exclusion of 88 irrelevant items. As a result, 34 relevant articles were extracted from 2014 to 2024. Hence, concise information on these papers is illustrated in Table 2.

Kim and Kim (1997) initially used the combination approach of EGT-SD to analyse the dynamic interaction between policies and drivers. According to the second column of Table 2, its further applications in SCM issues can be divided into five categories: (i) Policy development under regulations toward sustainability (47.5%), (ii) policy and incentive analysis (22.5%), (iii) safety and risk management (20%), (iv) economic impact analysis (15%), and (v) sector-specific and technological analysis (12.5%). As depicted, the first two classes have been trending more since 2014. Interestingly, we contributed to innovatively highlighting this trend by developing a model.

Based on the third column of Table 2, economic, environmental, and social sustainability pillars have been studied by 100%, 65%, and 15% of scholars, respectively. Indeed, 62.5% of researchers, such as (Tian et al., 2014), simultaneously focused on economic and environmental pillars. Unfortunately, the whole TBL matrices have been rarely emphasised by 2.5%; thus, more investigation is required. Moreover, the frequency of identified sustainability measures for each pillar is as follows. The economic facets included cost (97.5%), profit (97.5%), payoff (97.5%), revenue (15%), property (2.5%), and product quality (2.5%). Next, the environmental aspect covered weather pollution, GHG (or carbon) emission (38.4%), environmental pollution (19.2%), energy consumption (19.2%), green products or technology (11.5%), water pollution and consumption (3.8%), natural resources (15.3%), waste and recycling (11.5%), and wastewater (3.8%). Finally, the social pillar involved safety (33.3%), safe products (33.3%), and health (33.3%). Interestingly, this study would emphasise critical trend criteria (e.g., cost, profit, payoff, CO_2 emission and neutralisation), rarely used measures (e.g., waste such as expired medication quantities), and neglected ones (e.g., market demand and job creation).

With Table 2s fourth column in mind, recent studies worked on just one type of evolutionary game model. For instance, PCG and TEG have been two popular types with 25% and 67.5% frequency of use, respectively. Likewise, the Quadrilateral type is another rarely used one (2.5%). Although Tian et al. (2014) employed the PCG model, innovatively applying a combination of two trend types, e.g., PCG and TEG, is a neglected EGT model development area targeted by this study, considering the complexity of the real market competition. PCG is typically used to analyse pairwise interactions between two types in a single population (Yu et al., 2022). In contrast, TEG extends this framework to capture the complex, multi-player interactions among three populations (Pan et al., 2024). Combining these two models would bridge the gap between simplified pairwise interactions and the intricate, multi-actor dynamics of real-world SCs, allowing simultaneously account for the strategic behaviours inside and among multiple populations of stakeholders and their interdependent decision-making processes. This hybrid model provides a robust theoretical foundation for understanding how sustainability practices simultaneously diffuse either inner SC tiers or across SC echelons.

Moreover, according to the next two columns of Table 2, the government is a principal player in recent models employed by 67.5% of the scholars. Not surprisingly, 12.5% of

Table 2 A review of hybrid EGT and SD research

References	Contribution	Sustainability measures			Type of evolutionary game			Players	Stakeholders	Case study
		Economic	Environmental	Social	Pairwise contest	Tripartite	Quadrilateral			
Tian et al. (2014)	Subsidy guidance to promote the diffusion of green SC	Cost, Profit, payoff	Green products	–	✓			Manufacturers	Customers, government	Automotive industry
Liu et al. (2015)	Improve coal mining safety inspection process	Cost, profit, payoff	–	Safe product		✓		Local governments, Coal enterprises, State administration of coal mine safety	–	Coal mine safety inspection system
Zhang (2016)	Risk analysis of finance closed loop SCs	Cost, profit, payoff	–	–	✓			Upstream, midstream, downstream, Commercial banks	Small and medium-sized enterprises	SMEs
Duan et al. (2016)	Environmental regulation strategy development	Cost, profit, payoff	Environmental pollution	–		✓		Social, governments, enterprises	–	–
Zhao et al. (2016)	Investigation of possible responses to incentive policies	Cost, profit, payoff	Green products	–	✓			Enterprises	Government, customers	Air conditioner enterprises
Bai and Zhang (2018)	Position and operated results analysis	Cost, revenue, payoff	–	–	✓			Restaurants, galleries	–	Galleries and restaurants
Jiang et al. (2018)	Effective regulation strategies development	Cost, revenue, payoff	–	–		✓		Retailers, group buying platforms, consumers	Government	Online group-buying

Table 2 (continued)

References	Contribution	Sustainability measures			Type of evolutionary game			Players	Stakeholders	Case study
		Economic	Environmental	Social	Pairwise contest	Tripartite	Quadrilateral			
Ma and Hu (2018)	Evaluate the environmental effects of policies	Cost, Profit, payoff	Water pollution, GHG emissions	Human health				Government, enterprises, farmers	–	The pulp and paper industry
Li et al. (2019)	Inspection rate analysis	Cost, Profit, payoff		Safety		✓		High-speed railways, state railway administration, commissioned railways bureau	Government	Railway industry
Zhou et al. (2019)	Evaluation of the impact of policy incentives on electric vehicles development	Cost, revenue, payoff	Carbon emission, energy consumption	–	✓			Manufacturers, consumers	Government	Electric vehicle industry
Zhang et al. (2019)	Government policy analysis	Cost, Profit, payoff	GHG emissions, green technology	–	✓			governments, manufacturers	–	–
Feng et al. (2020)	Public supervision mechanism introduction	Cost, revenue, payoff	–	Safe products		✓		Public, governments, China railway	–	Railway industry
You et al. (2020)	Analyse coal mine safety regulation	Cost, revenue, payoff	–	–		✓		Coal mine owners, safety regulation departments, miners	Coal enterprises	Coal-mine enterprise

Table 2 (continued)

References	Contribution	Sustainability measures			Type of evolutionary game			Players	Stakeholders	Case study
		Economic	Environmental	Social	Pairwise contest	Tripartite	Quadrilateral			
Zhu et al. (2020)	Evaluate the impact of renewable portfolio standards on the retail electricity market	Cost, profit, payoff	Renewable energy	–		✓		Regulators, power sales companies	–	Retail electricity market
Yuan et al. (2020)	Provide a solution to the transboundary water-sharing problem	Cost, revenue, payoff	Water consumption	–	✓			Countries	–	Transboundary river basins
Zhu et al. (2020)	Manage urban food waste	Cost, profit, payoff	Waste, recycling	–		✓		Government departments, restaurants, waste disposal companies	–	Food industry
Qiu et al. (2021)	Simulate the mechanism of the cross-regional coordinated dispatch of emergency supplies	Cost, profit, payoff	–	–		✓		Local administration of emergency, emergency logistics enterprises, higher-level administration of emergency	–	Emergency supplies
Wang et al., (2021a, 2021b)	Promote environmental sustainability development of ecotourism	Cost, profit, payoff	Environmental pollution	–		✓		Local governments, tourism enterprises, residents	–	Ecotourism construction industry

Table 2 (continued)

References	Contribution	Sustainability measures			Type of evolutionary game			Players	Stakeholders	Case study
		Economic	Environmental	Social	Pairwise contest	Tripartite	Quadrilateral			
Wang et al., (2021a, 2021b)	Make a balance and evolution in a green technological system	Cost, profit, payoff	Resources, environmental pollution	–		✓		Government, enterprises, consumers	–	Engineering devices market
Shi et al. (2021)	Guide effective wildfire disaster management strategies	Property	–	Health		✓		Local governments, residents	–	Wildfires
Li et al. (2022)	Providing solutions to facilitate the implementation of solid waste categorisation policies	Cost, profit, payoff	Solid waste	–		✓		Government, society, residents	–	China
Eghbali et al. (2022)	Analysis of strategies for implementing green technology innovation under government intervention	Cost, profit, payoff	Resources, environmental pollution	–		✓		Government, startups	–	Green entrepreneurial ecosystem
Guo et al. (2022)	Investigation and simulation of the Biomass energy supply chain with carbon capture and storage	Cost, profit, payoff	Carbon emission	–		✓		Government, enterprises, third parties	–	China

Table 2 (continued)

References	Contribution	Sustainability measures			Type of evolutionary game			Players	Stakeholders	Case study
		Economic	Environmental	Social	Pairwise contest	Tripartite	Quadrilateral			
Han and Yang (2022)	Integrated analysis of profit distribution and stability in a common distribution system	Cost, profit, payoff	Carbon emission	–		✓		Government, enterprises	–	Logistic industry
Yu et al. (2022)	Unified analysis of renewable portfolio standards and green certificate trading	Cost, profit, payoff	Energy consumption	–	✓			Government, enterprises	–	Electricity producers
Singh and Mukherjee (2022)	Designing a penalty-reward system for environmentally supportive projects	Cost, profit, payoff	–	–		✓		Project portfolio manager, project manager, environmental manager	–	Projects of environment advocators
Guo (2023)	Examining the reasons for the failure of regional environmental protection inspections and the functioning of central environmental protection inspections	Cost, profit, payoff	Environmental degradation	–		✓		Central and local governments, enterprises	–	China
Liu and Li (2023)	Model development for addressing pollution from livestock and poultry	Cost, profit, payoff	Pollution, recycling	–			✓	Livestock and poultry farmers, third parties, consumers, government	–	Livestock industry

Table 2 (continued)

References	Contribution	Sustainability measures			Type of evolutionary game			Players	Stakeholders	Case study
		Economic	Environmental	Social	Pairwise contest	Tripartite	Quadrilateral			
Sheng et al. (2023)	Selecting coastal power generation strategies for ships by shareholders	Cost, profit, payoff	Weather pollution, energy consumption	–		✓		Government, port and shipping companies	–	Port and shipping industry of China
Shan et al. (2023)	Governance analysis of participatory urban crisis management in complex systems	Cost, profit, payoff	–	–		✓		Government, enterprises, public	–	China
Zuo et al. (2023)	Exploring government regulation strategies and stakeholders in the online ride-sharing industry	Cost, profit, payoff	–	–		✓		Online platforms, drivers, passengers	–	Online software for transportation
Song et al. (2023)	Developing a cooperative mechanism for carbon capture, utilisation, and storage	Cost, profit, payoff	Carbon emission	–		✓		Government, upstream and downstream operators	–	China
Nie et al. (2024)	Investigating stakeholder strategies in electric vehicle battery recycling	Cost, profit, payoff	Carbon emission, waste, recycling	–		✓		local governments, battery cathode manufacturers, battery pack manufacturers	–	Electric vehicles industry in China

Table 2 (continued)

References	Contribution	Sustainability measures			Type of evolutionary game			Players	Stakeholders	Case study
		Economic	Environmental	Social	Pairwise contest	Tripartite	Quadrilateral			
Pan et al. (2024)	Expanding the incentive mechanism for prefabricated buildings	Cost, profit, payoff	Natural resources	–		✓		Government, contractors, consumers	–	Prefabricated buildings projects
Current study	Diffusing sustainability across PSC under the pressure of both market and non-market stakeholders and impacts of a global pandemic like COVID-19	Cost, profit, market demand, payoff	CO_2emission and neutralisation of expired medication quantities	Job creation	✓	✓		Regulatory enterprises, retailers, distributors	Government, consumers	Iranian (Tehran) pharma industry

studies involved regulators as one of the players and imagined government as a stakeholder. Besides, 30% of the research included a population of enterprises as the other players. Nonetheless, only 22.5% of studies have addressed SC members as players. Manufacturers have been mainly emphasised in 55.5% of studies (Tian et al., 2014). Therefore, inserting REs, Ds and Rs as three players' populations and government and consumers as two influential stakeholders is another novelty of this paper.

Keeping the last column of Table 2in mind, the case study of recent research is divided into a country (20%), industry (30%), enterprises (30%) like SMEs and startups, project (5%) such as prefabricated building and environment advocator, and market (7.5%) including carbon and engineering devices. In detail, China is a popular country in this domain. However, Iran is a low-income emerging economy that has not yet been considered. Besides, the reviewed articles focused on industries such as automotive, electric vehicle, railway, food, construction, etc. Nonetheless, the pharma industry has not been addressed through its critical multi-faceted role in regional development and the detrimental impacts of environmental pollution (EFPIA, 2023). Thus, the Iranian pharmaceutical industry has been selected as a case study to address these drawbacks, validating the developed EGT-SD model.

3 Model

As illustrated in Fig. 1, SSCM diffuses across upstream (Ds) and downstream PSC (Rs) under pressure from non-market (government and REs) and market stakeholders (SC members and consumers). Unforeseen events, like a global pandemic, can influence this process and consumer demand. Initially, the government establishes sustainability policies and a

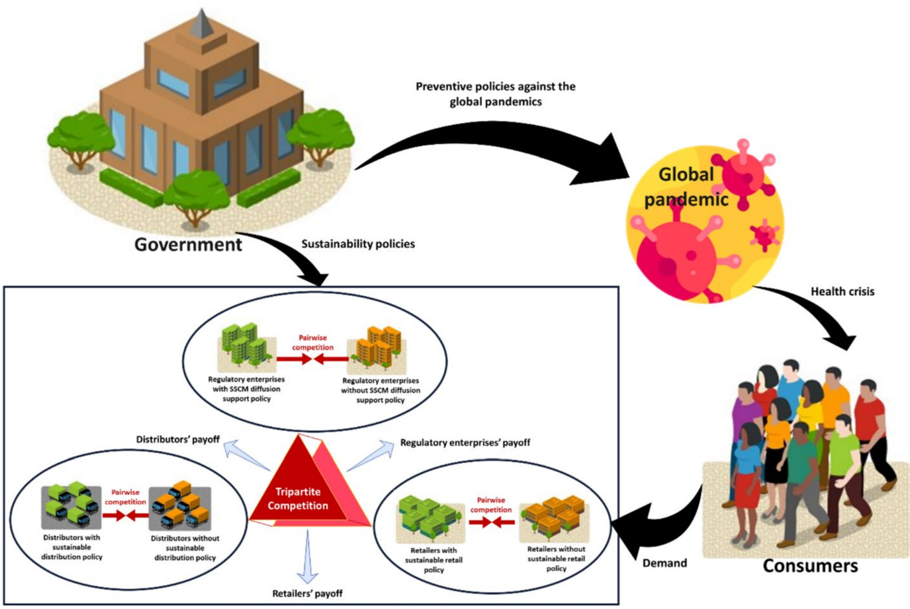


Fig. 1 Sub-system diagram of SSCM diffusion mechanism under interventions of REs

budget for their downstream REs to oversee the spread of sustainable development across PSC members. Consequently, REs enforce these policies by supervising SC members' operations, providing subsidies and rewards, and imposing fines. In reality, some REs, despite receiving funds, may avoid implementation due to low payoff when the total supervision costs, subsidies, and rewards surpass the total budget and fines. Thus, there is observable pairwise competition between REs supporting sustainability diffusion policies and those who do not. Similarly, there is significant pairwise competition at each level of the upstream and downstream PSC, Ds, and Rs. In general, Ds may choose to follow a sustainable distribution policy or not, and Rs are free to adopt a sustainable retail policy. These decisions are made by evaluating and comparing each strategic choice's payoffs. Ultimately, these three pairwise competitions are valuable for gauging the dynamic changes in each population (i.e., REs and PSC members (Ds, Rs)). Not surprisingly, the payoff of each strategic choice for all three populations depends on others' decisions. As a result, a tripartite competition among these players must be considered, computing their payoff function based on real-world complex market competition.

The SSCM diffusion evolutionary game parties are then set as $i = (1, 2, 3)$, where $i = 1$ reflects the REs, $i = 2$refers to the Ds, and $i = 3$represents the Rs. Additionally, each of the three PCG models is rooted in a finite set of two pure strategies $S_i = \{G_i, N_i\}$, $(i = 1, 2, 3)$. Hence, each party has a finite set of two pure strategies. Specifically,

- REs $(i = 1)$can choose to support SSCM diffusion $(G_1)$by monitoring practices, imposing fines, and providing rewards and subsidies, or not supporting it (N_1).
- Ds $(i = 2)$can adopt sustainable distribution practices (G_2), which include clean transportation, job opportunity creation, real-time inventory monitoring, and reducing expired products, or opt for non-sustainable practices (N_2).
- Rs $(i = 3)$can implement sustainable retail practices (G_3), focusing on job opportunity creation, real-time inventory monitoring, and reducing expired products, or choosing non-sustainable practices (N_3).

It is logical for the nature of the strategies to be similar, as both G_2 and G_3 pertain to sustainable practices. However, these strategies' costs and implementation requirements differ significantly for each echelon (Ds and Rs). This distinction arises from their unique roles and responsibilities within the SC. For instance, Ds incur additional costs related to clean transportation, which is not a concern for Rs. Conversely, Rs focus more on end-user interactions and inventory management. Thus, while the overarching goal of sustainability aligns both strategies, the specific actions, costs, and challenges vary based on their operational contexts.

The probability of each party selecting $G_i$is signed by X_{G_i}, while the probability of selecting $N_i$is $X_{N_i} = 1 - X_{G_i}$. Each party aims to maximise its expected payoff, where $U_{G_i}$and U_{N_i}represent the payoff functions for selecting $G_i$and N_i, respectively. Additionally, the successful implementation of a strategy depends on the party's assets and capabilities. Thus, PI_i denotes the probability of each party's successful implementation of the strategy. The following assumptions were considered before developing the PCG models.

Assumption 1 The whole number of each party's population is fixed.

Assumption 2 All parties imagined bounded rationality. Hence, optimal strategy and payoff functions are gradually obtained over long-term learning and evolving strategy selection. Each RE (or D or R) (i) selects a certain pure strategy for every time unit, (ii) then accidentally samples a representative from the population with similar probability for all REs (or Ds or Rs), (iii) next reviews their strategy and compares the representative's payoff with their own, and (iv) occasionally decides to change the strategy until they obtain the optimal one.

Assumption 3 Presume the $i^{th}$and j^{th}player, in case the discrepancy between their payoff $(U_i - U_j)$is negative, then the i^{th}player will switch to the j^{th}player's strategy with the probability of $\#\,(U_i - U_j)$as below (Tian et al., 2014).

$$\#\,(U_i - U_j) = \begin{cases} (U_i - U_j)/U_i & if\ U_i - U_j < 0 \\ 0 & if U_i - U_j \geq 0 \end{cases} \quad (i,j) = (G_i, N_i)\,for\,(i = 1,2,3). \tag{1}$$

It is noteworthy that $X_{G_i}$and X_{N_i} $(X_{N_i} = 1 - X_{G_i})$are a function of time (t). For instance, when D slowly changes the strategy, the imitation speed of the rest of the population is slow. Through time derivatives, three dynamic changing rates of (i) REs' probability with SSCM diffusion support policy ($\dot{X}_{G_1}$), (ii) Ds' probability with sustainable distribution policy ($\dot{X}_{G_2}$), and (iii) Rs' probability with sustainable retail policy ($\dot{X}_{G_3}$) can be calculated using the replicator dynamics equations of the pairwise contest EGT as follows (Tian et al., 2014):

$$(i)BRRE = \dot{X}_{G_1} = X_{G_1}\,(1 - X_{G_1})\,[\#\,(U_{G_1} - U_{N_1}) - \#\,(U_{N_1} - U_{G_1})] \times PI_1 \tag{2}$$

$$(ii)BRD = \dot{X}_{G_2} = X_{G_2}\,(1 - X_{G_2})\,[\#\,(U_{G_2} - U_{N_2}) - \#\,(U_{N_2} - U_{G_2})] \times PI_2 \tag{3}$$

$$(iii)BRR = \dot{X}_{G_3} = X_{G_3}\,(1 - X_{G_3})\,[\#\,(U_{G_3} - U_{N_3}) - \#\,(U_{N_3} - U_{G_3})] \times PI_3 \tag{4}$$

A TEG model was innovatively employed to estimate six expected payoff functions used in the above equations. This TEG model operates based on the mixed strategy sets in Fig. 2.

Suppose that REs, Ds, and Rs employ G_1, G_2, and G_3, respectively, with a probability of $X_{G_{1,2,3}}\left(0 \leq X_{G_{1,2,3}} \leq 1\right)$, where $X_{G_{1,2,3}} = 0$denotes no SSCM diffusion support and no sustainable distribution and retail implementation, respectively. Conversely, $X_{G_{1,2,3}} = 1$

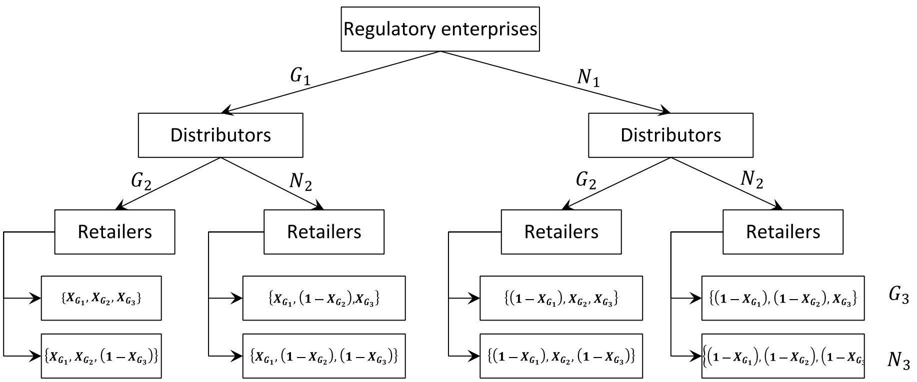


Fig. 2 Mixed strategic choices in the TEG model

denotes the highest level of SSCM diffusion support and sustainable distribution and retail implementation, respectively. Accordingly, eight potential mixed strategies can be formed. Besides, the further variables applied in estimating U_{G_i} and U_{N_i} are defined in Table 3.

With this in mind, the TEG model's payoff matrix, illustrated in Table 4, was created based on eight combinations resulting from two pure strategy options for each player, REs, Ds, and Rs. Logically, the payoff is the difference between expenses and income. This general logic has been applied here to generate this payoff matrix. Each player incurs certain costs (CREG, CDG, CRG) and earns profits (PDG, PRG). Besides, GB serves as a source of income for the REs. However, the GB was allocated among REs based on their outcome, indicating the number of Ds and Rs with $G_{i=2,3}$. For instance, if all Ds and Rs follow (or do not follow) $G_{i=2,3}$, REs will receive the total funds (or zero). Note that the allocated budget for the rest of the status has been computed based on experts' opinions and the REs' outcome.

Generally, the Ds and the Rs generate total sales profits as their main revenue. Their number of sales is equivalent to the difference between their total demand and expired products. For instance, if one of the Ds selects G_2, its sales profits will be equal to $\left(\frac{TDDG-EMQDG}{DG} \times TPDG\right)$. Not surprisingly, unmet demand due to expired products represents a hidden cost for the Ds and the Rs. For instance, if one of the Ds selects G_2, their lost demand costs will be computed as $\left(\frac{EMQDG}{DG} \times TPDG\right)$. Additionally, fines (FDG, FDN, FRG, and FRN) contribute to the income of the REs, but they are expenses for the Ds and the Rs. Conversely, rewards (RDG and RRG) and subsidies (SDG and SRG) are both expenses for the REs, while rewards serve as income for the Ds and the Rs, and subsidies act as customers' sustainable purchase profits.

Using the payoff matrix (Table 4), the strategies chosen by two other players and their respective probabilities have been considered to formulate each expected payoff function. Correspondingly, U_{G_i} and U_{N_i} for $i = 1, 2, 3$ were defined as Eqs. (5) to (10) as follows.

$$\begin{aligned}
U_{G_1} = {} & X_{G_2}X_{G_3}\Big[-RDG - RRG - CREG + GB \\
& - \left(\frac{TDDG - EMQDG}{REG} \times SDG \times APSPD\right) \\
& - \left(\frac{TDRG - EMQRG}{REG} \times SRG \times APSPR\right)\Big] \\
& + X_{G_2}\left(1 - X_{G_3}\right)\Big[-RDG + FDG + FRN - CREG + GB \\
& - \left(\frac{TDDG - EMQDG}{REG} \times SDG \times APSPD\right)\Big] \\
& + \left(1 - X_{G_2}\right)X_{G_3}\Big[FDN - RRG + FRG - CREG + GB \\
& - \left(\frac{TDRG - EMQRG}{REG} \times SRG \times APSPR\right)\Big] \\
& + \left(1 - X_{G_2}\right)\left(1 - X_{G_3}\right)\left[FDN + FRN - CREG + GB\right]
\end{aligned} \tag{5}$$

$$\begin{aligned}U_{G_2} = {} & X_{G_1}X_{G_3}\,[RDG - FDG - CDG + PDG \\ & + \left(\frac{TDDG - EMQDG}{DG} \times TPDG\right) - \left(\frac{EMQDG}{DG} \times TPDG\right)\Big] \\ & + X_{G_1}(1 - X_{G_3})\,[RDG - FDG - CDG + PDG \\ & + \left(\frac{TDDG - EMQDG}{DG} \times TPDG\right) - \left(\frac{EMQDG}{DG} \times TPDG\right)\Big] \\ & + (1 - X_{G_1})\,X_{G_3}\left[-CDG + PDG + \left(\frac{TDDG - EMQDG}{DG} \times TPDG\right) - \left(\frac{EMQDG}{DG} \times TPDG\right)\right] \\ & + (1 - X_{G_1})(1 - X_{G_3})\left[-CDG + PDG + \left(\frac{TDDG - EMQDG}{DG} \times TPDG\right) - \left(\frac{EMQDG}{DG} \times TPDG\right)\right]\end{aligned} \tag{6}$$

$$\begin{aligned}U_{G_3} = {} & X_{G_1}X_{G_2}\,[RRG - FRG - CRG + PRG \\ & + \left(\frac{TDRG - EMQRG}{RG} \times SPRG\right) - \left(\frac{EMQRG}{RG} \times SPRG\right)\Big] \\ & + (1 - X_{G_1})\,X_{G_2}\left[-CRG + PRG + \left(\frac{TDRG - EMQRG}{RG} \times SPRG\right) - \left(\frac{EMQRG}{RG} \times SPRG\right)\right] \\ & + X_{G_1}(1 - X_{G_2})\,[RRG - FRG - CRG + PRG \\ & + \left(\frac{TDRG - EMQRG}{RG} \times SPRG\right) - \left(\frac{EMQRG}{RG} \times SPRG\right)\Big] \\ & + (1 - X_{G_1})(1 - X_{G_2})\,[-CRG + PRG \\ & + \left(\frac{TDRG - EMQRG}{RG} \times SPRG\right) - \left(\frac{EMQRG}{RG} \times SPRG\right)\Big]\end{aligned} \tag{7}$$

$$U_{N_1} = X_{G_2}X_{G_3}\,[GB] + X_{G_2}(1 - X_{G_3})\left[\frac{GB}{4}\right] + (1 - X_{G_2})\,X_{G_3}\left[\frac{3GB}{4}\right] + (1 - X_{G_2})(1 - X_{G_3})\,[0] \tag{8}$$

$$\begin{aligned}U_{N_2} = {} & X_{G_1}X_{G_3}\left[-FDN + \left(\frac{TDDN - EMQDN}{DN} \times TPDN\right) - \left(\frac{EMQDN}{DN} \times TPDN\right)\right] \\ & + X_{G_1}(1 - X_{G_3})\left[-FDN + \left(\frac{TDDN - EMQDN}{DN} \times TPDN\right) - \left(\frac{EMQDN}{DN} \times TPDN\right)\right] \\ & + (1 - X_{G_1})\,X_{G_3}\left[\left(\frac{TDDN - EMQDN}{DN} \times TPDN\right) - \left(\frac{EMQDN}{DN} \times TPDN\right)\right] \\ & + (1 - X_{G_1})(1 - X_{G_3})\left[\left(\frac{TDDN - EMQDN}{DN} \times TPDN\right) - \left(\frac{EMQDN}{DN} \times TPDN\right)\right]\end{aligned} \tag{9}$$

$$\begin{aligned}U_{N_3} = {} & X_{G_1}X_{G_2}\left[-FRN + \left(\frac{TDRN - EMQRN}{RN} \times SPRN\right) - \left(\frac{EMQRN}{RN} \times SPRN\right)\right] \\ & + (1 - X_{G_1})\,X_{G_2}\left[\left(\frac{TDRN - EMQRN}{RN} \times SPRN\right) - \left(\frac{EMQRN}{RN} \times SPRN\right)\right] \\ & + X_{G_1}(1 - X_{G_2})\left[-FRN + \left(\frac{TDRN - EMQRN}{RN} \times SPRN\right) - \left(\frac{EMQRN}{RN} \times SPRN\right)\right] \\ & + (1 - X_{G_1})(1 - X_{G_2})\left[\left(\frac{TDRN - EMQRN}{RN} \times SPRN\right) - \left(\frac{EMQRN}{RN} \times SPRN\right)\right]\end{aligned} \tag{10}$$

As an example, Eq. (5), the expected payoff for REs when selecting strategy G_1, was calculated as the weighted sum of the payoffs associated with strategy G_1, considering the strategies chosen by Ds and Rs ($G_{i=2,3}$and $N_{i=2,3}$), and their respective probabilities ($X_{Gi=2,3}$and $X_{Ni=2,3}$). The breakdown of Eq. (5) includes four parts: (i) $\left[-RDG - RRG - CREG + GB - \left(\frac{TDDG-EMQDG}{REG} \times SDG \times APSPD\right) - \left(\frac{TDRG-EMQRG}{REG} \times SRG \times APSPR\right)\right]$ indicates REs' payoff when they select G_1, Ds select G_2, and Rs select G_3, (ii) $\left[-RDG + FDG + FRN - CREG + GB - \left(\frac{TDDG-EMQDG}{REG} \times SDG \times APSPD\right)\right]$ denotes REs' payoff when they select G_1, Ds select G_2, and Rs select N_3, (iii)

Table 3 List of variables employed in payoff matrix of TEG model

Party	Variable	Definition	Note
REs	*REG*	Number of REs with G_1	$0 \geq REG \geq (REG + REN)$
	REN	Number of REs with N_1	$0 \geq REN \geq (REG + REN)$
	CREG	Costs occurred by REs responding to the implementation of G_1	$CREG > 0$
	GB	Governmental budget	$GB > 0$
Ds	*DG*	Number of Ds with G_2	$0 \geq DG \geq (DG + DN)$
	DN	Number of Ds with N_2	$0 \geq DN \geq (DG + DN)$
	CDG	Costs occurred by Ds responding to the implementation of G_2	$CDG > 0$
	PDG	Profits obtained by Ds implementing G_2	$PDG \geq 0$
	RDG	REs give rewards to Ds with G_2	$RDG \geq 0$
	FDG	Fines imposed by REs to Ds with G_2	$0 \leq FDG \leq FDN$
	FDN	Fines imposed by REs to Ds with N_2	$FDN \geq 0$
	APSPD	Ds' average product sales price	$APSPD \geq 0$
	TPDG	Transportation profit per product obtained by Ds implementing G_2	$TPDG \geq 0$
	TPDN	Transportation profit per product obtained by Ds implementing N_2	$TPDN \geq 0$
	SDG	Subsidy per product for purchasing from Ds with G_2	$SDG \geq 0$
	TDDG	Total demand from Ds with G_2	$TDDG \geq 0$
	TDDN	Total demand from Ds with N_2	$TDDN \geq 0$

Table 3 (continued)

Party	Variable	Definition	Note
	$EMQDG$	Expired medication quantities of Ds with G_2	$0 \leq EMQDG < EMQDN$
	$EMQDN$	Expired medication quantities of Ds with N_2	$EMQDN \geq 0$
Rs	RG	Number of Rs with G_3	$0 \geq RG \geq (RG + RN)$
	RN	Number of Rs with N_3	$0 \geq RN \geq (RG + RN)$
	CRG	Costs occurred by Rs responding to the implementation of G_3	$CRG > 0$
	PRG	Profits obtained by Rs implementing G_3	$PRG \geq 0$
	RRG	REs give rewards to Rs with G_3	$\mathrm{RRG} \geq 0$
	FRG	Fines imposed by REs to Rs with G_3	$0 \leq FRG \leq FRN$
	FRN	Fines imposed by REs to Rs with N_3	$FRN \geq 0$
	$APSPR$	Rs' average product sales price	$APSPR \geq 0$
	$SPRG$	Sales profits per product obtained by Rs implementing G_3	$SPRG \geq 0$
	$SPRN$	Sales profits per product obtained by Rs implementing N_3	$SPRN \geq 0$
	SRG	Subsidy per product for purchasing from Rs with G_3	$SRG \geq 0$

Table 3 (continued)

Party	Variable	Definition	Note
	TDRG	Total demand from Rs with G_3	$TDRG \geq 0$
	TDRN	Total demand from Rs with N_3	$TDRN \geq 0$
	EMQRG	Expired medication quantities of Rs with G_3	$0 \leq EMQRG < EMQRN$
	EMQRN	Expired medication quantities of Rs with N_3	$EMQRN \geq 0$

Table 4 Payoff matrix of tripartite EGT model

Party		Regulatory enterprises X_{G_1}	$(1-X_{G_1})$		Party
Retailer	X_{G_3}	$-RDG - RRG - CREG + GB - (\frac{TDDG-EMQDG}{REG} \times SDG \times APSPD) - (\frac{TDRG-EMQRG}{REG} \times SRG \times APSPR)$, $RDG - FDG - CDG + PDG + (\frac{TDDG-EMQDG}{DG} \times TPDG) - (\frac{EMQDG}{DG} \times TPDG)$, $RRG - FRG - CRG + PRG + (\frac{TDRG-EMQRG}{RG} \times SPRG) - (\frac{EMQRG}{RG} \times SPRG)$	GB, $-CDG + PDG + (\frac{TDDG-EMQDG}{DG} \times TPDG) - (\frac{EMQDG}{DG} \times TPDG)$, $CRG + PRG + (\frac{TDRG-EMQRG}{RG} \times SPRG) - (\frac{EMQRG}{RG} \times SPRG)$	X_{G_2}	Distributor
	$(1-X_{G_3})$	$-RDG + FDG + FRN - CREG + GB - (\frac{TDDG-EMQDG}{REG} \times SDG \times APSPD)$, $RDG - FDG - CDG + PDG + (\frac{TDDG-EMQDG}{DG} \times TPDG) - (\frac{EMQDG}{DG} \times TPDG)$, $-FRN + (\frac{TDRN-EMQRN}{RN} \times SPRN) - (\frac{EMQRN}{RN} \times SPRN)$	$\frac{GB}{4}$, $-CDG + PDG + (\frac{TDDG-EMQDG}{DG} \times TPDG) - (\frac{EMQDG}{DG} \times TPDG)$, $(\frac{TDRN-EMQRN}{RN} \times SPRN) - (\frac{EMQRN}{RN} \times SPRN)$		
	X_{G_3}	$FDN - RRG + FRG - CREG + GB - (\frac{TDRG-EMQRG}{REG} \times SRG \times APSPR)$, $-FDN + (\frac{TDDN-EMQDN}{DN} \times TPDN) - (\frac{EMQDN}{DN} \times TPDN)$, $RRG - FRG - CRG + PRG + (\frac{TDRG-EMQRG}{RG} \times SPRG) - (\frac{EMQRG}{RG} \times SPRG)$	$\frac{3GB}{4}$, $(\frac{TDDN-EMQDN}{DN} \times TPDN) - (\frac{EMQDN}{DN} \times TPDN)$, $-CRG + PRG + (\frac{TDRG-EMQRG}{RG} \times SPRG) - (\frac{EMQRG}{RG} \times SPRG)$	$(1-X_{G_2})$	
	$(1-X_{G_3})$	$FDN + FRN - CREG + GB$, $-FDN + (\frac{TDDN-EMQDN}{DN} \times TPDN) - (\frac{EMQDN}{DN} \times TPDN)$, $-FRN + (\frac{TDRN-EMQRN}{RN} \times SPRN) - (\frac{EMQRN}{RN} \times SPRN)$	0, $(\frac{TDDN-EMQDN}{DN} \times TPDN) - (\frac{EMQDN}{DN} \times TPDN)$, $(\frac{TDRN-EMQRN}{RN} \times SPRN) - (\frac{EMQRN}{RN} \times SPRN)$		

$\left[FDN - RRG + FRG - CREG + GB - \left(\frac{TDRG - EMQRG}{REG} \times SRG \times APSPR\right)\right]$ represents REs' payoff when they select G_1, Ds select N_2, and Rs select G_3, and (iv) $[FDN + FRN - CREG + GB]$shows REs' payoff when they select G_1, Ds select N_2, and Rs select N_3. This logic has been employed in computing other expected payoff functions (Eqs. (6) to (10)). Therefore, the six payoff functions (Eqs. (5) to (10)) resulting from the developed TEG model have been ready to put in the replicator dynamics equations of the pairwise contest EGT (Eqs. (2) to (4)), completing the evolutionary game model construction phase.

Then, instead of an exact method, a simulation approach, SD, was employed to dynamically solve the developed combined EGT model. Indeed, the long-run dynamic evolution of SSCM diffusion behind the developed EGT models has been simulated through SD-based EGT models. As such, the SD-EGT model covers three chief modules: (i) SSCM diffusion, (ii) parties' payoff, and (iii) consumer market impacted by global pandemics similar to COVID-19. The first two modules were interconnected, under pressure from the third module. In this vein, each module was initially modelled and compiled to accomplish the integrated SD-EGT model. To this end, the below stepwise process has occurred via the VENSIM software.

(i) The main variables regarding three replicator dynamics equations were recognised [Eqs. (2) to (4)], six payoff functions [Eqs. (5) to (10)], and the supply–demand cycle principle (Mahdiraji et al., 2021, 2022a; Tavana et al., 2020) impacted by the COVID-19 outbreak. Apart from the variables employed in EGT models, the complementary variables of the SD-EGT model were discovered, as demonstrated in Table 5.

(ii) The cause-and-effect interactions between all identified variables were explored. The Casual Loop Diagram (CLD) for each module was then depicted. Afterwards, the whole CLD was obtained by assembling them. Next, each module's Stock Flow Diagram (SFD) was depicted by distinguishing stocks and flows. The stock variables contain REG, REN, DG, DN, RG, RN, and POP. Conversely, the flow variables include DRRE, DRD, DRR, NPGR, NPDR, and PDCOV. The whole SFD, illustrated in Fig. 3, was reached by compiling the module's SFD.

(iii) The integrated SD-EGT model was constructed, and the stock flows and auxiliaries equation was determined. To this end, Eqs. (2) to (10) and the Cobb–Douglas demand function with two variables of price and marketing (Mahdiraji et al., 2021, 2022b; Tavana et al., 2020) have been employed. The Cobb–Douglas demand function is preferred for several key reasons. This issue has not been modelled under stochastic or probabilistic conditions; therefore, employing a deterministic demand function is imperative. Considering Cobb and Douglas (1928), firstly, the Cobb–Douglas demand function's simplicity and analytical tractability make it easy to work with, both in analytical and computational contexts. When transformed logarithmically, the function yields linear relationships, facilitating the derivation of elasticities and other analyses. Secondly, the function encapsulates important economic principles, such as diminishing marginal returns and the substitutability between inputs. The coefficients in the Cobb–Douglas function represent output elasticities that sum to one, indicating constant returns to scale—an assumption prevalent in many economic models. Furthermore, extensive empirical validation has shown that the Cobb–Douglas function often fits the data quite well, contributing to its widespread acceptance and historical use

Table 5 List of further variables employed in the SD-EGT model

Module	Variable	Definition	Note
SSCM diffusion	*TRRE*	REs dynamic changing rate after G_1 implementation	$0 \leq TRRE \leq 1$
	TRD	Ds dynamic changing rate after G_2 implementation	$0 \leq TRD \leq 1$
	TRR	Rs dynamic changing rate after G_3 implementation	$0 \leq TRR \leq 1$
	SDRE	Delay of switching to G_1	$SDRE > 0$
	SDD	Delay of switching to G_2	$SDD > 0$
	SDR	Delay of switching to G_3	$SDR > 0$
	DRRE	SSCM diffusion support/not support rate in REs	$0 \leq DRRE \leq 1$
	DRD	The diffusion rate of sustainable/unsustainable distributing	$0 \leq DRD \leq 1$
	DRR	The diffusion rate of sustainable/unsustainable retailing	$0 \leq DRR \leq 1$
	RCRE	Resource capability of REs	$RCRE > 0$
	RCD	Resource capability of Ds	$RCD > 0$
	RCR	Resource capability of Rs	$RCR > 0$
Parties' payoff	*PECDG*	Product expiration coefficient of Ds with G_2	$PECDG < PECDN$
	PECDN	Product expiration coefficient of Ds with N_2	$PECDN > PECDG$
	PECRG	Product expiration coefficient of Rs with G_3	$PECRG < PECRN$
	PECRN	Product expiration coefficient of Rs with N_3	$PECRN > PECRG$
	DECDG	Direct CO_2emission coefficient of Ds with G_2	$DECDG < DECDN$
	DECDN	Direct CO_2emission coefficient of Ds with N_2	$DECDN > DECDG$
	DRECDG	Direct reduced CO_2emission coefficient of Ds with G_2	$DRECDG > 0$
	JCDG	Job opportunity creation of Ds with G_2	$JCDG > 0$
	JCRG	Job opportunity creation of Rs with G_3	$JCRG > 0$
	TEDG	Transportation tCO_2e emission of Ds with G_2	$0 \leq TEDG < TEDN$
	TEDN	Transportation tCO_2e emission of Ds with N_2	$TEDN \geq 0$
	TREDG	Transportation tCO_2e reduced the emission of Ds with G_2	$TREDG \geq 0$
	TJCDG	Total job opportunity creation of Ds with G_2	$TJCDG > 0$
	TJCRG	Total job opportunity creation of Rs with G_3	$TJCRG > 0$
	FEPG	Fines per expired product imposed by REs to Ds with G_2(or Rs with G_3)	$0 \leq FEPG < FEPN$
	FEPN	Fines per expired product imposed by REs to Ds with N_2(or Rs with N_3)	$FEPN \geq 0$

Table 5 (continued)

Module	Variable	Definition	Note
	FEDG	Fines per tCO_2e emission imposed by REs to Ds with G_2	$0 \leq FEDG < FEDN$
	FEDN	Fines per tCO_2e emission imposed by REs to Ds with N_2	$FEDN \geq 0$
	RERDG	Rewards per tCO_2e emission reduction given by REs to Ds with G_2	$RERDG \geq 0$
	RJCG	Rewards per job opportunity creation given by REs to Ds with G_2(or Rs with G_3)	$RJCG > 0$
	ACRG	Average cost per product of Rs with G_3	$ACRG > 0$
	ACRN	Average cost per product of Rs with N_3	$ACRN > 0$
	DRGDG	The demand for Rs with G_3 from Ds with G_2	$DRGDG \geq 0$
	DRGDN	The demand for Rs with G_3 from Ds with N_2	$DRGDN \geq 0$
	DRNDG	The demand for Rs with N_3 from Ds with G_2	$DRNDG \geq 0$
	DRNDN	The demand for Rs with N_3 from Ds with N_2	$DRNDN \geq 0$
The consumer market impacted by the global pandemic	*POP*	Population	$POP > 0$
	NPGR	Net population growth rate	$0 < NPGR < 1$
	NNBR	Normal net birth rate per person	$NNBR > 0$
	NPDR	Net population death rate	$NPDR \geq 0$
	PDRCOV	Population death rate due to the COVID-19 outbreak	$PDRCOV \geq 0$
	LT	Lifetime per person	$LT \geq 0$
	FCOVIR	Function of the COVID-19 infection rate	$FCOVIR \geq 0$
	COVIR	The COVID-19 infection rate	$COVIR \geq 0$
	FCOVDR	Function of the COVID-19 death rate	$FCOVDR \geq 0$
	COVNDR	The COVID-19 normal death rate	$COVNDR = 1$
	COVDR	The COVID-19 death rate	$COVDR \geq 0$
	FCOVNBR	Function of the COVID-19 impact on the net birth rate	$COVNBR \geq 0$
	NBRICCOV	The net birth rate increased coefficient impacted by the COVID-19	$BRIC \geq 0$
	NCR	Normal consumption rate per person	$NCR > 0$
	FCOVCR	Function of the COVID-19 impact on the consumption rate per person	$FCOVCR \geq 0$
	CRICCOV	Consumption rate per person increased coefficient impacted by the COVID-19	$CRICCOV \geq 0$

Table 5 (continued)

Module	Variable	Definition	Note
	NAPSPR	Rs normal average product sales price	*NAPSPR*= 1
	VCDG	Cost of advertising sustainable products by Ds with G_2	*VCDG*< *CDG*
	VCRG	Cost of advertising sustainable products by Rs with G_3	*VCDG*< *CRG*
	NVCDG	The normal cost of advertising sustainable products by Ds with G_2	*NVCDG*= 1
	NVCRG	The normal cost of advertising sustainable products by Rs, with G_3	*NVCRG*= 1
	Alpha1	Product sales price elasticity of retailers with G_3	$0.01 \leq Alpha1 \leq 1.5$
	Alpha2	Product sales price elasticity of retailers with N_3	$0.01 \leq Alpha2 \leq 1.5$
	Beta1	Advertisement elasticity of distributors with G_2	$0.7 < Beta1 < 1$
	Beta2	Advertisement elasticity of retailers with G_3	$0.\ 7 < Beta1 < 1$
	CD	Consumers demand	*CD*> 0

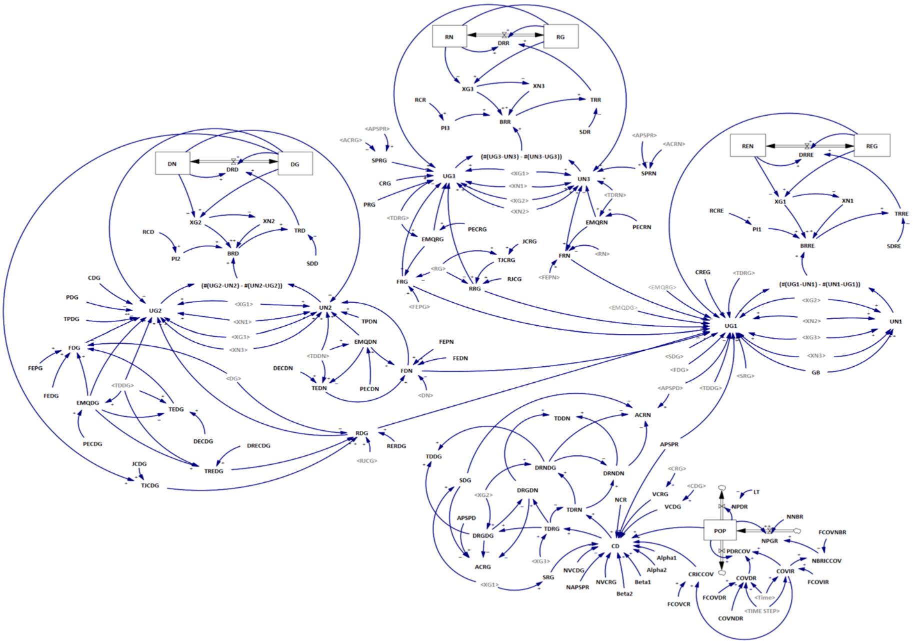


Fig. 3 The SFD of SSCM diffusion upstream and downstream of the pharmaceutical industry

as a solid foundation for ongoing application. Finally, the functional form is versatile and can be easily extended to include additional inputs or more complex structures, such as integrating two variables: price and marketing (Reynés, 2019). However, other functional forms may introduce unnecessary complexity without significantly enhancing the model's fit (Diewert & Wales, 1987). For instance, translog functions or more sophisticated stochastic models can capture more nuanced relationships, yet they often present challenges in estimation and interpretation (Reynés, 2019). To avoid confusion, a complete list of variables, their type, equations, and the unit has been provided in Appendix 1.

Data collation This paper employed primary and secondary data. The primary data was collected through interviews with sample experts. The population from which our sample was drawn consisted of professionals working in the pharma industry within the specified categories of job positions, education, and fields of study across universities, pharmacies, and medical distribution enterprises. Although we do not have an exact number for the entire population, the experts selected represent a significant cross-section of this professional community. We employed a snowball sampling procedure to select our sample. This method was particularly effective given the specialised nature of our target population. Initial subjects, known for their qualifications, were identified and interviewed. These initial subjects then referred other experts who met our criteria, thus expanding our sample pool. Snowball sampling ensured that we included well-connected and knowledgeable individuals who might not have been easily accessible through other sampling methods. Experts' qualifications included (i) The experts specialised in management, industrial engineering, or pharmacology; (ii) The educational qualifications of the experts included an MSc, PhD, or a Doctor of Pharmacy degree; (iii) The experts were employed at universities, pharmacies, or medical distribution enterprises. (iv) The experts held significant positions such as CEO, Human Resource Manager, Marketing Manager, Financial Manager, Pharmaceutical Visitor, or Academic Staff, and (v) Each expert had at least three years of working experience in the pharma industry.

To gather the raw data, several in-depth interviews with 35 experts with the above profile (Table 6) were conducted, each lasting at least one hour. The rationale for conducting interviews with 35 experts stems from the snowball sampling method, wherein each participant referred other suitably qualified experts. This iterative referral process continued until data saturation was achieved, signifying that, after the 35th interview, no additional significant information or novel insights were forthcoming. Consequently, the decision was made to cease further interviews, as the collected data was deemed sufficient and comprehensive for this study. Besides, the valid extant documents and reports were used to collect the secondary data.

Table 6 Experts profile

Number of Experts	Field of study	Level of Education	Working Industry	Job position	Working experience (years)
2	Management	MSc	Pharmacy	Pharmaceutical visitor	5
1	Management	MSc	Pharmacy	Pharmaceutical visitor	7
3	Management	MSc	Pharmacy	Pharmaceutical visitor	4
2	Management	MSc	Pharmacy	Financial manager	5
2	Pharmacology	Doctor of Pharmacy	Pharmacy	Financial manager	3
1	Pharmacology	Doctor of Pharmacy	University, Pharmacy	CEO, academic staff	2
5	Industrial Engineer	PhD	University, Pharmacy	CEO, academic staff	5
4	Pharmacology	Doctor of Pharmacy	University, Pharmacy	CEO, academic staff	4
2	Management	MSc	Medical distribution enterprise	Financial manager	5
3	Pharmacology	Doctor of Pharmacy	University, medical distribution enterprise	Pharmaceutical visitor	7
4	Management	MSc	Medical distribution enterprise	Human resource manager	5
1	Management	PhD	University, medical distribution enterprise	Human resource manager, academic staff	2
3	Industrial Engineer	MSc	Medical distribution enterprise	Marketing Manager	6
2	Management	MSc	Medical distribution enterprise	Marketing Manager	8

4 Initial simulation results

The developed SD-EGT model has been simulated to investigate how SSCM diffuses upstream and downstream of a PSC during and after a global pandemic like COVID-19. Tehran's pharmaceutical industry (capital of Iran) has been examined as the case study. Note that this study focused on 12 specific products (zinc tablet: 1, vitamin C effervescent tablet and capsules: 4, vitamin C and zinc tablet and capsules: 3, general multi-vitamins tablet and capsules: 4). Based on expert views, these products strengthen the body's immune system and have been requested more since COVID-19 emergence, even without prescription. To run the simulation, firstly, the initial values of stocks and parameters, demonstrated in Table 7, were extracted from the extant valid documents[1]and statistical reports in March 2020, coinciding with the emergence of the COVID-19 outbreak (e.g., (i) World Health Organization COVID-19 dashboard[2]; (ii) Executive Regulations[3]; (iii) Clause (J), (iv) Article (104) of the Law of the Third Plan of Economic, Social, and Cultural Development of the Islamic Republic of Iran[4]; (v) the budget law of 2022 of Iran[5]; (vi) the third chapter (population) of the statistical yearbook of Tehran province[6]; and (vii) the yearbook of population statistics[7]), and interviews with the experts with profiles as Table 6.

Three enterprises have regulated Iran's pharmaceutical industry. Only one of them advocates sustainable development policies. Sustainable and unsustainable upstream and downstream PSC enterprises have yet to be distinguished. This paper revealed this void by investigating the initial values of their sustainable criteria. Inevitably, several meetings were held with experts to do so. Eventually, those who had lower coefficients of expired products and CO_2emissions, some job creation, and CO_2neutralisation were placed in the sustainable class. Although these enterprises had to pay more, they profited from implementing this strategy. Nonetheless, cleaner transportation profit per product was slightly lower than uncleaned. In either case, the average product sale price was equal. Accordingly, more than half of the upstream tiers (37 of 49) followed N_2, and the rest (12) pursued G_2. Likewise, downstream PSC included 1548 tiers, 817 confirmed $N_3$and 713 followed G_3. On average, the players' delay time for learning and switching $G_{i=1,2,3}$was estimated at 1.5 months based on experts' unanimity.

Further, the initial values of the Cobb–Douglas demand function parameters were determined based on model logical justification and experts' opinions. Generally, advertisement demand elasticity should be a maximum of 0.2. However, if Betas 1 and 2 are less than 0.7, the probability of selecting G_3will be more than 1. This breaks model rationality. On the other hand, based on experts' views, these values cannot be beyond 0.7. Besides, enterprises cannot liberally change the sale price in the PSC to prove that simulation results are the same when these values change from low to high. However, sustainable enterprises can supply products at lower prices by applying subsidies obtained from REs with G_1. This indicates

[1] http://necjournals.ir/article-1-462-fa.html, https://sanad.iau.ir/fa/Article/839765, https://doi.org/10.22054/eenr.2007.6996.

[2] https://data.who.int/dashboards/covid19/cases.

[3] https://qavanin.ir/Law/TreeText/?IDS=12738515587594829611.

[4] https://rc.majlis.ir/fa/law/show/93301.

[5] http://cdn.meybod.ac.ir/blog/userfiles/financial/files/financial_7.pdf.

[6] https://amar.thmporg.ir/.

[7] https://amar.org.ir/salnameh-amari/agentType/ViewType/PropertyTypeID/623.

Table 7 Initial values of the stocks and parameters (Stock (s); Constant (c))

Variable ID	Type	Initial value	Unit	Variable ID	Type	Initial value	Unit
REG	S	1	Enterprise	**FEPN**	C	0.01	Million Rials/Product
REN	S	2	Enterprise	**FEDG**	C	1.8	Million Rials/TCO2e
DG	S	12	Enterprise	**FEDN**	C	1.8	Million Rials/TCO2e
DN	S	37	Enterprise	**RERDG**	C	0	Million Rials/TCO2e
RG	S	731	Enterprise	**RJCG**	C	0	Million Rials/Employee
RN	S	817	Enterprise	**CREG**	C	2,260	Million Rials/(Month*Enterprise)
POP	S	13.8071	Million People	**CDG**	C	8,122	Million Rials/(Month*Enterprise)
RCRE	C	0.8	Dmnl	**CRG**	C	412	Million Rials/(Month*Enterprise)
RCD	C	0.57	Dmnl	**GB**	C	3,000	Million Rials/(Month*Enterprise)
RCR	C	0.46	Dmnl	**PDG**	C	8,200	Million Rials/(Month*Enterprise)
SDRE	C	RANDOM NORMAL (0, 3, 1.5, 0.1, 0)	Month	**PRG**	C	420	Million Rials/(Month*Enterprise)
SDD	C	RANDOM NORMAL (0, 3, 1.5, 0.1, 0)	Month	**TPDG**	C	0.182333	Million Rials/Product
SDR	C	RANDOM NORMAL (0, 3, 1.5, 0.1, 0)	Month	**TPDN**	C	0.25	Million Rials/Product
PECDG	C	0.025	Dmnl	**NNBR**	C	0.0010516	1/Month
PECDN	C	0.075	Dmnl	**LT**	C	744	Month
PECRG	C	0.0017	Dmnl	**NCR**	C	42.48	(Product/Month)/Million People
PECRN	C	0.0084	Dmnl	**APSPD**	C	0.771083	Million Rials/Product
DECDG	C	0.0392	TCO2e/Product	**APSPR**	C	1.05383	Million Rials/Product
DECDN	C	0.05375	TCO2e/Product	**Alpha1**	C	0.03	Dmnl
DRECDG	C	0.01455	TCO2e/Product	**Alpha2**	C	0.01	Dmnl
JCDG	C	4	Employee/(Month*Enterprise)	**Beta1**	C	0.7	Dmnl
JCRG	C	1	Employee/(Month*Enterprise)	**Beta2**	C	0.7	Dmnl
FEPG	C	0.01	Million Rials/Product				

Iran's currency was used

that advertisements can severely impact downstream preference for sustainable enterprises. Indeed, advertising a medication with a slightly lower sale price has more demand elasticity.

Secondly, the validation and verification tests were performed. Indeed, structural validation tests, including structure assessment and dimensional consistency, were performed using the VENSIM software. Consequently, two messages received from the software (i.e., "Model is OK" and "Units are OK") confirmed the validity of the SD-EGT model structure. Moreover, models were verified with extreme condition tests, e.g., sensitivity analysis and a behaviour reproduction test.

Sensitivity analysis checks model robustness by applying uncertainty to model assumptions. It can be performed for three types based on Sterman (2000): (i) numerical sensitivity, (ii) behaviour mode sensitivity, and (iii) policy sensitivity. Generally, all models are numerically sensitive. Nonetheless, the second type will occur when a change in parametric assumption leads to a change in simulated behaviour, e.g., alteration from goal-seeking to oscillation. The third will eventuate when a change in parametric assumption reverses the impacts or utility of one policy. The second and third sensitivity tests were frequently performed in the scenario analysis phase (Sect. 5) to provide a policy-making system for diffusing SSCM in PSC. Moreover, root mean square percentage error (RMSPE) and Theil's inequality statistics or inequality coefficient (U) have been calculated by Eqs. (11) and (12) for different variables to test the reproduction of the model behaviour.

$$RMSPE = \sqrt{\frac{1}{n}\sum\nolimits_{t=1}^{n}\left(\frac{S_t - A_t}{A_t}\right)^2} \tag{11}$$

$$U = \sqrt{\frac{1}{n} \times \frac{\sum\nolimits_{t=1}^{n}(S_t - A_t)^2}{\left(\left(\sum\nolimits_{t=1}^{n} A_t^2\right) + \left(\sum\nolimits_{t=1}^{n} S_t^2\right)\right)}} \tag{12}$$

where $n$represents the number of studied periods. $A_t$and $S_t$denote the real and simulated values of the considered variable in $t$time, respectively. The model behaviour reproduction is confirmed if RMSPE is less than 0.5 or U is close to zero. Otherwise, it is not verified. For instance, RMSPE and U are calculated in Table 8for the auxiliary variable of TJCDG.

The outcomes of both tests align with the criteria for acceptance, thus validating the model. Consequently, adjustments were made to the model's time settings, including setting the units for time to months, the initial time to zero (indicating March 2020), the final time to 240, and the time step to one. The simulation was executed with these settings. As a result, A simulated mixed strategy equilibrium solution (Eq. (13)) was accomplished for the integrated PCG and TEG in that period. Moreover, six payoffs (Eq. (14)) were simulated at this equilibrium point.

$$\begin{aligned} X_{G_i}{}^* &= (X_{G_1}{}^*, X_{G_2}{}^*, X_{G_3}{}^*) = (0.00432931 \sim 0, 0.56152, 0.973764) \\ X_{N_i}{}^* &= (X_{N_1}{}^*, X_{N_2}{}^*, X_{N_3}{}^*) = (0.995671 \sim 1, 0.43848, 0.0262364) \end{aligned} \tag{13}$$

$$\begin{aligned} U_{G_i}{}^* &= (U_{G_1}{}^*, U_{G_2}{}^*, U_{G_3}{}^*) = (809.57, 374.393, 23.2888) \\ U_{N_i}{}^* &= (U_{N_1}{}^*, U_{N_2}{}^*, U_{N_3}{}^*) = (2612.11, 363.57, 15.0832) \end{aligned} \tag{14}$$

Table 8 Calculation of RMSPE and U for the auxiliary variable of TJCDG

n	A_t	S_t	$\left(\frac{S_t - A_t}{A_t}\right)^2$	$(S_t - A_t)^2$	A_t^2	S_t^2
1	40	48.7	0.05	22.6	1936	2,377.6
2	43	49.6	0.04	21.3	2025	2,462.1
3	44	49.9	0.04	24.8	2025	2,498.5
4	45	50.4	0.04	29.8	2025	2,546.5
5	46	50.9	0.04	24.1	2116	2,592.5
6	47	51.3	0.03	18.9	2209	2,636.9
7	48	51.6	0.03	32.1	2116	2,669.6
8	49	52. 1	0.03	16.6	2304	2,712.3
9	50	52.4	0.03	12.2	2401	2,755.8
10	51	52.9	0.03	15.3	2401	2,800.3
11	52	53.2	0.03	10.6	2500	2,837.1
12	53	53.5	0.03	12.4	2500	2,864.7
Summation			0.42	264.1	27,054	31,754.2

$RMSPE = 0.4, U = 0.000019$

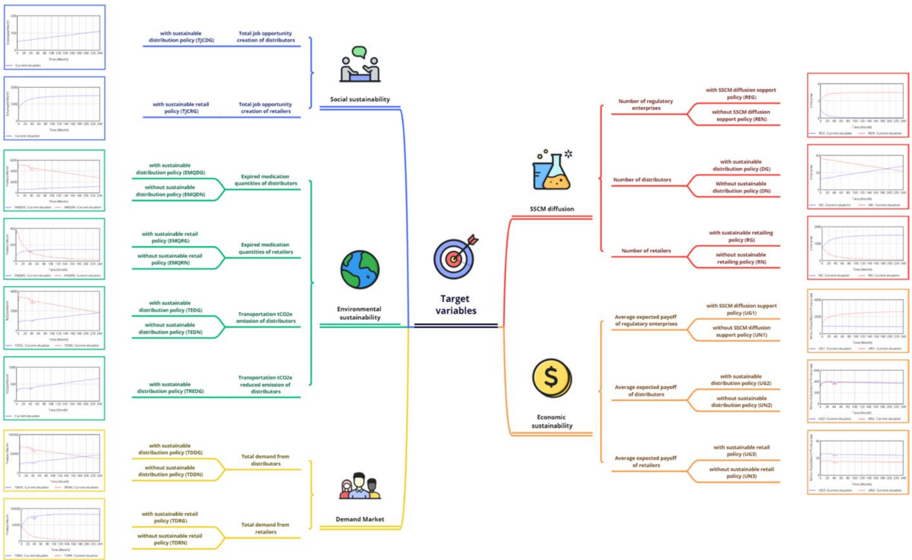


Fig. 4 A comprehensive simulated picture of the case study's current situation (March 2020 to 2039) (Please note that Appendix 2contains some diagrams in a more visible format)

More precisely, 25 target variables were divided into five categories, including **SSCM diffusion**(REG, REN, DG, DN, RG, RN), **economic sustainability**($U_{G_{i=1,2,3}}$, $U_{N_{i=1,2,3}}$), **social sustainability**(TJCDG, TJCDN), **environmental sustainability**(EMQRG, EMQRN, EMQDG, EMQDN, TEDG, TEDN, TREDG), and **market demand**(TDRG, TDRN, TDDG, TDDN). Consequently, Fig. 4illustrates a comprehensive simulated picture of the case study's current situation from March 2020 to March 2039.

Health protocols and COVID-19 lockdowns limited the monitoring activities of RE with G_1, especially in the first 20 months. During this period, RE with G_1noticed the natural increase in DG and RG and his counterparts' permanent sharply climbing payoff. Hence, REG sharply decreased by the twentieth month. Afterwards, this tendency continued with a lower slope, and a steady state was reached by about 2028. REN inversely mirrored this pattern. Moreover, DG linearly increased and surrounded more than half of the upstream tiers (28 of 49). Besides, RG significantly escalated by the twentieth month; this sentiment extended with a moderate slope until the sixtieth month, and then a perpetual slight growth led to 1,507 Rs with G_3in a steady state in the last month. Conversely, DN and RN decreased to approximately 21 and 41, respectively.

Economically, despite the same behaviour of each tier's payoff upstream and downstream, $U_{Gi=1,2}$was always less than $U_{Ni=1,2}$. This stems from demand from each tier. However, CD experienced a sharp rise and fall during COVID-19. In the post-COVID-19, it will still be higher than before this pandemic. Consequently, the number of sales is a prominent element of profitability. However, it decreases as much as expired products. This highlights the connection between economic and environmental sustainability. **Ecologically**, increasing DG and RG led to a descending trend of expired medication upstream and downstream. Finally, each echelon expired 157 and 3,941 products monthly, respectively. Moreover, upstream transportation CO_2emissions diminished to around 3,633 monthly TCO2e. Besides, carbon neutralisation of this level escalated to a monthly level of 669 TCO2e. Importantly, eco-friendliness has evolved into a consistent practice in both the upstream and downstream sectors, even when there were low penalties for emissions or no rewards for neutralisation. **Socially**, growing DG and RG resulted in an ascending behaviour of job opportunities upstream and downstream. Finally, each echelon was able to post 110 and 1,507 vacancies monthly. Indeed, creating job opportunities was an economic and social solution to handle an increased workload for further CD and remote and part-time job positions due to COVID-19's side effects (e.g., lockdowns, short working times, etc.). Fortunately, this reaction continued even after COVID-19. Hence, it became a social responsibility of 0.562 of upstream and 0.974 of downstream enterprises.

5 Scenario analysis and implications

Policy-making via scenario analysis is a well-applied technique to journey from unideal to ideal status. The desirability of our case study will occur if SSCM entirely diffuses upstream and downstream. A simulated pure strategy equilibrium solution $X_{Gi=1,2,3}=(1, 1, 1)$ must be accomplished immediately. Unfortunately, by following the extant policies, a pure strategy equilibrium solution $X_{Gi=1,2,3}=(0.0002\sim0, 0.99\sim1, 0.99\sim1)$ would be simulated in a prolonged future (by 2228). Still worse, REG will be zero even at that point. Nonetheless, several benchmarked countries set a timeline for realising the SSCM diffusion theory. For instance, the developed regions (e.g., the United States, Britain, Canada, and Japan) are targeted to reach carbon neutrality by 2050. Moreover, as a developing country, China aimed at various implementation plans for carbon peak and neutrality by 2030 and 2060, respectively (Zhao et al., 2022).

Ergo, this section contributes to a well-end policy-making process to promote SSCM diffusion in Tehran's PSC. In so doing, testing five scenarios on the developed EGT-SD model was planned to simulate an ideal picture of this case study. Each scenario, illustrated in Fig. 5, was defined to compensate for one of the extant regulation voids: (i) non-

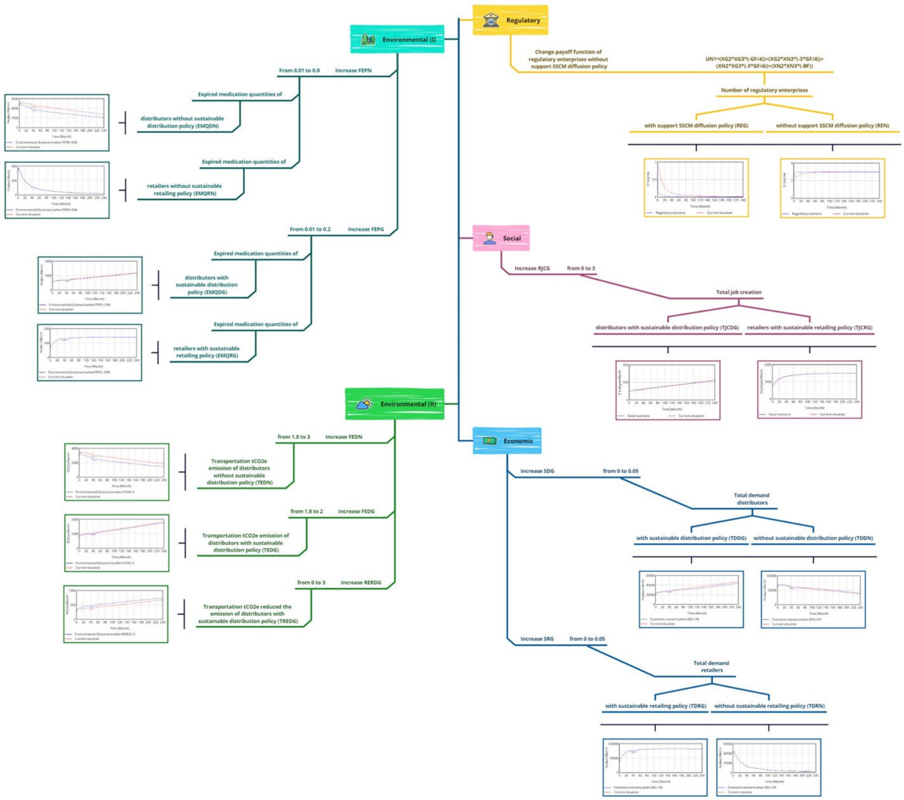


Fig. 5 Scenario analysis results (Please note that Appendix 3contains some diagrams in a more visible format)

separation of sustainable and unsustainable enterprises based on sustainable development goals and standards; (ii) no distinction between even low punishment of Ds and Rs with $G_{i=2,3}$and $N_{i=2,3}$for CO_2emissions and expired products; (iii) no reward given to Ds and Rs with $G_{i=2,3}$for creating jobs and reducing CO_2emissions; (iv) no subsidy granted to Ds, Rs, and consumers for purchasing from sustainable enterprise. Legislatively, giving any GB to REs with $N_1$is not authentic, even if Ds and Rs instinctively followed $G_{i=2,3}$. However, fines should be imposed on them in the case of the converse. In this regard, advocating SSCM diffusion theory would become legitimate. Hence, $U_{N1}$was changed to Eq. (15).

$$U_{N_1} = X_{G_2} X_{G_3}\left[-\frac{GF}{4}\right] + X_{G_2}\left(1 - X_{G_3}\right)\left[-\frac{3GF}{4}\right] + \left(1 - X_{G_2}\right) X_{G_3}\left[-\frac{3GF}{4}\right] + \left(1 - X_{G_2}\right)\left(1 - X_{G_3}\right)[-GF] \quad (15)$$

GF indicates governmental fines imposed on REs with $N_2$for eluding regulations related to SSCM diffusion theory. Next, the EGT-SD model was changed accordingly. The environmental impact of increasing FEPN (or FEPG) on EMQDN and EMQRN (or EMQDG and EMQRG) was simulated. Note that even a bit of a distinction was considered between punishments imposed on Ds and Rs with $G_{i=2,3}$and $N_{i=2,3}$. Generally, followers of sustainable development goals should pay fewer fines than their counterparts. Hence, FEPG and FEPN were elevated to 0.2 and 0.9, respectively. The effect of extending FEDG to two and FEDN to three was investigated on TEDG and TEDN, respectively. Besides, RERDG was escalated from zero to three. Then, its impact on TERDG was evaluated. Socially, the influence of amplifying RJCG from zero to three was investigated on TJCRG and TJCDG. Economically, the subsidy was considered for Ds and Rs with $G_{i=2,3}$to sell their products with a discount. To this end, SDG and SRG were raised from zero to 0.05. The effect of this action was assessed on TDDG, TDDN, TDRG, and TDRN.

Ergo, by separately implementing the regulatory scenario, REG not only would not increase but would sharply diminish. Besides, by increasing rewards for job creation, TJCDG and TJCRG would grow a bit compared to the current situation. Moreover, TDRG and TDRN would drop slightly as SRG grows. Conversely, TDDG would negligibly decrease from the 60th month by increasing SDG. Plus, imposing more fines for expired products and CO_2emissions would negatively impact EMQDN and TEDN more negatively than EMQDG, EMQRG, EMQRN, and TEDG. Additionally, giving rewards to Ds with $G_2$for their CO_2emissions reduction would considerably affect cleaner transportation. Consequently, exclusivity in closed-loop systems may even lead to worse behaviour. Hence, holism and a systemic view must accomplish such systems' ideal behaviour. The case study's ideal status would be obtained in Fig. 6by applying the five scenarios above. In this regard, A mixed strategy equilibrium solution was achieved as Eq. (16). Each party's payoff related to this equilibrium point is demonstrated in Eq. (17). Expectedly, a simulated pure strategy equilibrium solution $X_{Gi=1,2,3}$=(0.99~1, 1, 0.99~1) would also be achieved by 2056.

$$
\begin{aligned}
X_{G_i}{}^* &= (X_{G_1}{}^*, X_{G_2}{}^*, X_{G_3}{}^*) = (0.991976 \sim 1, 1, 0.979344) \\
X_{N_i}{}^* &= (X_{N_1}{}^*, X_{N_2}{}^*, X_{N_3}{}^*) = (0.008024 \sim 0, 0, 0.0206556)
\end{aligned}
\tag{16}
$$

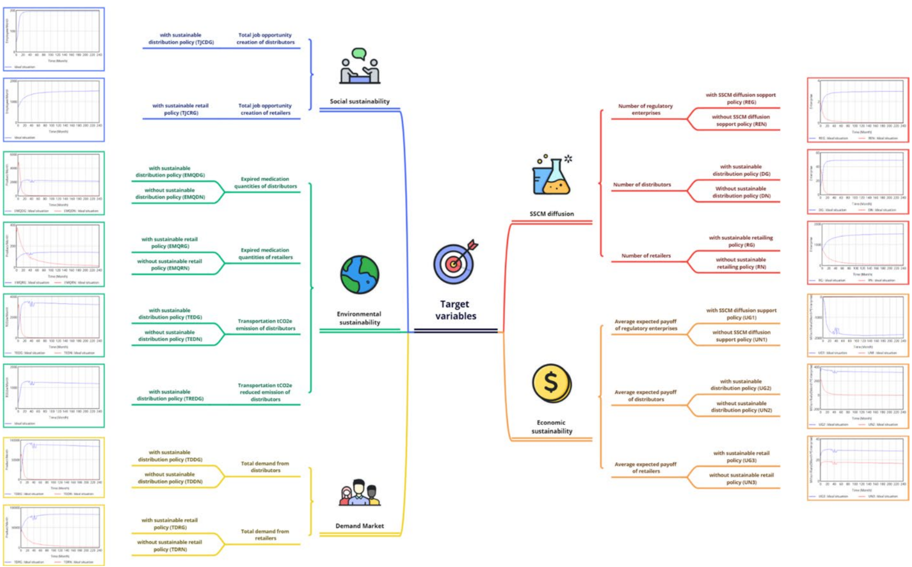


Fig. 6 A comprehensive simulated picture of the case study's ideal situation (March 2020 to 2039) (Please note that Appendix 4contains some diagrams in a visible format)

$$U_{G_i}{}^* = (U_{G_1}{}^*, U_{G_2}{}^*, U_{G_3}{}^*) = (-1833.85, 321.054, 28.3579)$$
$$U_{N_i}{}^* = (U_{N_1}{}^*, U_{N_2}{}^*, U_{N_3}{}^*) = (-7.28852, -4.15066, 16.7589) \tag{17}$$

Eliminating the extant regulation voids mainly impacts REs and upstream behaviour diagrams. Hopefully, REG will sharply increase by the twentieth month. After that, this trend will continue with a lower slope, and a steady state will be reached by 2026. Surprisingly, U_{G1}will be less than U_{N1}in this period. This indicates the substitution of financial goal priority with advocating sustainable development policies. Despite the slow linear growth of U_{N1}, U_{G1}will significantly ascend in the long term. Similarly, DG will abruptly climb by the 20th month. This growth will maintain with a slight slope, and then a steady state will occur by 2024. It is expected that U_{N2}will considerably fall in the first 20 months. Besides, $U_{N2}$is always less than U_{G2}.

From a **market lens**, TDDG will rise harshly in this period. Its next fluctuation stems from the COVID-19 infection rate and its linear descending behaviour results from a decreasing population. **Environmentally**, the total amount of expired medication upstream will drop significantly to about 2,000 monthly products. Moreover, upstream transportation CO_2emissions will diminish to around 3,000 monthly TCO2e. Besides, Ds will upgrade carbon neutralisation to 1,194 TCO2e per month. **Socially**, the total vacancies created upstream will increase to about 200 monthly employees. Nonetheless, the downstream awareness associated with SSCM diffusion theory has been admirable. Interestingly, the downstream current and ideal behaviour diagrams are greatly the same. However, RG's growth intensity will be slightly higher than the current status. This stems from a bit higher U_{G3}. **Ecologically**, the downstream whole expired medications will roughly decrease to 154 monthly products. **Socially**, this echelon will desirably account for about 1,516 monthly job opportunities.

6 Conclusions and future recommendations

Diffusing SSCM is an appropriate solution to the worldwide concerns of the TBL, particularly neutralising the carbon footprint. Nonetheless, a comprehensive policy-making system embedded with a systemic view has been required. Simultaneously considering SC echelons and tiers, stakeholders' dynamic interactions, and the entire TBL pillars (people, planet, profit) have been greatly demanded. Theoretically, this paper mainly contributed to constructing such a system for the pharmaceutical industry by innovatively integrating two SLR streams and two types of EGT models (PCG and TEG) and SD.

The integration of PCG and TEG models is a novel theoretical approach that leverages the strengths of both models to better represent the dynamic interactions in and among multiple populations of stakeholders in PSCs. While PCG captures bilateral interactions between two species in a single population (Yu et al., 2022), TEG extends this by incorporating tripartite interactions among three populations (Pan et al., 2024). This combined perspective provides a more comprehensive understanding of the complexities within the PSC and government relationships. By integrating PCG and TEG, we establish a more robust theoretical framework for analysing the dynamic evolutionary stability of strategies, specifically the diffusion of sustainable practices, within multi-tiered (e.g., Ds) and across multi-echelon (e.g., Ds and Rs) PSCs, simultaneously. We incorporated SD modelling to strengthen our analysis further, providing several key advantages. First, SD allows us to

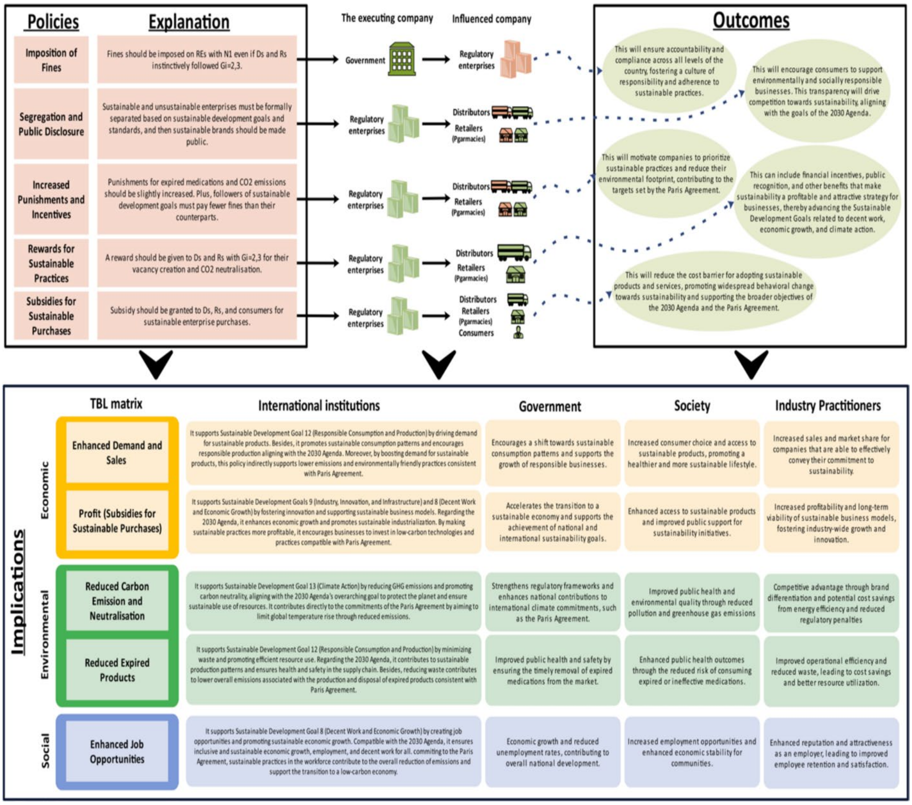


Fig. 7 Summary of recommended policies and their outcomes and implications

capture the dynamic and feedback-driven nature of stakeholder interactions over time, offering insights into how short-term decisions influence long-term outcomes. Second, it enables the simulation of complex scenarios, such as the impact of external shocks (e.g., pandemics) or policy interventions, on adopting sustainable practices. Third, SD complements the EGT models by translating strategic interactions into quantifiable outcomes, such as reductions in CO2 emissions or improvements in supply chain efficiency. Integrating PCG, TEG, and SD creates a powerful theoretical framework for understanding and managing the complexities of sustainable supply chain management diffusion in multi-tire-echelon-product-period PSCs (Tian et al., 2014).

Moreover, the side effects of the global COVID-19 pandemic were investigated, including its advent and outbreak times, as well as the aftermath. This industry's most essential TBL criteria were initially extracted by systematically reviewing the extant literature. These are the cost, profit, market demand, payoff, CO_2emissions and neutralisation, vacancy creation, and expired medication quantities. Upstream and downstream echelons and REs were recognised as the most prominent populations to study. Next, three PCGs were modelled to obtain three replicator dynamics equations. Afterwards, one TEG model was constructed to compute six payoffs used in those equations. Later, the SD-EGT model was developed to simulate the targeted policy-making system by considering stakeholders' interactions.

The developed model was employed to study how SSCM diffuses the echelons above Tehran's PSC. Managerially, scenario analysis was then applied to help Iran's PSC policymakers eliminate the extant regulation voids and arrive at the ideal status. Consequently, the side effects of a global pandemic could promote the SSCM diffusion theory. Nonetheless, holism must substitute exclusivity in amending the reward and punishment system. Eventually, a summary of recommended policies and their outcomes and implications is demonstrated in Fig. 7. Managerially, the following five policies are suggested to be simultaneously implemented. (**i**) Fines should be imposed on REs with N_1even if Ds and Rs instinctively followed $G_{i=2,3}$. (**ii**) Sustainable and unsustainable enterprises must be formally separated based on sustainable development goals and standards, and then sustainable brands should be made public. (**iii**) Punishments for expired medications and CO_2emissions should be slightly increased. Plus, followers of sustainable development goals must pay fewer fines than their counterparts. (**iv**) A reward should be given to Ds and Rs with $G_{i=2,3}$for their vacancy creation and CO_2neutralisation. (**v**) Subsidy should be granted to Ds, Rs, and consumers for sustainable enterprise purchases.

By imposing fines on non-compliant REs, the state-owned companies ensure accountability and compliance, fostering a culture of responsibility and adherence to sustainable practices throughout the governmental bodies in addition to PSC. Publicly recognising sustainable brands drives consumer support and healthy, transparent competition. Stricter penalties for expired medications and emissions, balanced with incentives, encourage companies to adopt sustainable practices. Rewarding job creation and CO_2neutralisation makes sustainability profitable, while subsidies for sustainable purchases remove cost barriers, fostering a widespread shift towards eco-friendly choices. These policies create a robust framework for a sustainable and resilient future, aligning with the sustainable development goals, the 2030 Agenda, and the Paris Agreement.

Considering the studied TBL measures, the practical implications of the recommended policies are substantial. Economically, implementing subsidies for sustainable purchases would boost demand, increase sales, and enhance profitability for companies committed to sustainability. Environmentally, these policies would significantly reduce carbon emissions, effectively neutralise efforts, and improve waste management, including expired products. Socially, creating new job opportunities within the sustainable sector would be successfully achieved, fostering economic growth and community development. More specifically, these policies would have far-reaching implications for various stakeholders (please see Fig. 7for in-depth information):

- **International Institutions**: Organisations such as the United Nations play a pivotal role in these policies, as they would see them as crucial steps towards achieving global sustainability goals. Their alignment with initiatives like the Sustainable Development Goals, the 2030 Agenda, and the Paris Agreement is not just important but integral to the success of these policies.
- **Government and REs**: Enhanced regulatory frameworks would be strengthened, ensuring compliance and incentivising sustainable practices, thereby supporting national and international sustainability commitments.
- **Society**: The public's health and welfare are at the forefront of these policies. They would improve through reduced pollution, better waste management, and increased employment, showing that their well-being is a top priority.

- **The pharma Industry Practitioners (PSC members like Ds and Rs)**: Companies would gain a competitive advantage through brand differentiation, operational efficiency, and cost savings. Investing in green technologies and sustainable practices would increase profitability and long-term viability.

Above all, some fundamental managerial suggestions can be made for each stakeholder, facilitating the implementation of the five proposed policies. Initially, the government should introduce Stringent Regulations and Monitoring Systems, implementing and enforcing regulations to ensure REs' compliance with sustainable development policies. Next, state-owned companies, like REs, should support Public Awareness Campaigns by funding and promoting them to highlight the importance of sustainable practices and the PSC's role in these efforts. As such, Educational Initiatives on Medication Disposal can be employed, informing the public about the dangers of expired medications and the importance of proper disposal. Furthermore, they should employ Public Recognition and Promotion, establishing certification programs and public awareness campaigns to recognise and promote sustainable enterprises. Subsequently, PSC members, Ds and Rs, should invest in Green Technologies such as drone delivery, energy-efficient processes, carbon offset programs, etc. Additionally, they should enhance Inventory Management Systems to minimise expired products and ensure compliance with regulations. Besides, they should prioritise Hiring and Training in sustainable practices by creating new roles dedicated to sustainability and environmental management. Furthermore, companies should engage in Transparent Marketing and Communication to attract environmentally conscious consumers. Finally, they could leverage Financial Support to reduce costs associated with sustainable practices and invest in further innovation and development.

Interestingly, this paper developed a **general SD-EGT model**of SSCM diffusion for the pharmaceutical industry. Despite these extensive efforts, several limitations were identified that future research should aim to address. Exploring these limitations can lead to more robust and comprehensive studies, deepening our understanding of PSC sustainability.

Firstly, the study's scope was limited to two echelons within the PSC: Ds and Rs, specifically pharmacies. Future research could expand this focus to include other critical echelons such as suppliers, primary and secondary manufacturers, and additional retailers like hospitals. This expanded scope would provide a more comprehensive understanding of PSC sustainability diffusion. Additionally, emphasising backward PSC echelons like remanufacturers could offer scholars new insights. Generally, a holistic approach to sustainability dissemination throughout a circular PSC could help mitigate negative impacts such as CO_2emissions and the accumulation of toxic waste and expired products. Moreover, other stakeholders, such as the press and NGOs, could be modelled to enhance the diffusion of SSCM practices. From a TBL perspective, although the study considered key TBL measures, other important sustainability metrics are identified in the fourth column of Table 1, warranting further investigation. These include product quality, lead time, delivery time, energy and natural resource consumption, recycling, wastewater management, water usage, staff and consumer satisfaction and health, workplace safety, and training. Future research should delve deeper into these measures to provide a more nuanced understanding of sustainability in PSCs.

Methodologically, the study employed an SLR to identify critical TBL measures. However, future researchers could benefit from additional data collection methods such as questionnaires, interviews, and case studies to identify these indicators. The final TBL measures in this study were selected based on frequency, but a fuzzy-Delphi approach could be useful for screening criteria according to experts' views. Furthermore, multi-criteria decision-making approaches could be employed to rank these criteria and assist in scenario analysis by levelling options. Despite this study's originality in integrating two types of EGT models (PCG and TEG), replacing the TEG with a quadrilateral evolutionary game model could benefit future scholars examining a PSC with more than two echelons. Additionally, while this study used SD as a digital twin for macro-level policy-making simulation, future researchers could focus on medium and micro-level simulations using agent-based and discrete-event modelling approaches.

The Cobb–Douglas demand function has been an effective choice in this analysis due to its simplicity, flexibility, and clear economic interpretation. However, like any functional form, it may not fully capture all potential complexities in demand behaviour. While this model provides valuable insights, future research could explore alternative deterministic or stochastic demand functions to refine demand estimates further. Additionally, relaxing the assumption of constant returns to scale or incorporating more dynamic elements could offer deeper perspectives on demand dynamics.

Another limitation of this study is the use of crisp numbers. Integrating uncertainty types such as neural fuzzy networks with the EGT-SD model could enhance the research output. While simulation was the unique solution method used here, future studies could solve the developed model through exact methods and compare the results to achieve more reliable outcomes. Furthermore, while the study used a case study and sensitivity analysis to validate the developed model, designing experiments based on data from existing documents could produce validated results applicable to other PSCs in developing and developed countries, enriching the scenario analysis phase. From a regulatory standpoint, this study employed subsidies, rewards, and fines as sustainability improvement policies. However, other schemes, such as taxes, cap-and-trade systems, cooperation contracts, etc., could be explored in future research. Moreover, this paper reduced CO_2emissions and expired products by only imposing fines and granting rewards. Nonetheless, future scholars could even diminish the coefficients of product expiration and direct CO_2emissions by adding **Digitalised SC Theory**to this model. The "**House of SC 4.0**", generated by Mahdiraji et al. (2022b), could be useful.

Technically, this study assumed that order and demand quantities were equal. Future research could apply different order and inventory systems to determine the ideal purchase quantity, enhancing the model's applicability.

Finally, due to the study's primary focus on the pharmaceutical industry, the general model was constructed based on essential TBL measures identified from research in sustainable PSCs. Future studies should run this model for other industries while carefully validating the sustainability measures to ensure their applicability across various sectors. Besides, the role of REs in this model (i.e., supervising, granting subsidies and rewards, and imposing fines) has been set based on the mission of legislative enterprises monitoring the pharma industry under the government. However, using such an assumption in other industries requires enough caution to acquire reliable results. By addressing these limitations, future research can build upon the current study's findings, offering a more comprehensive and nuanced understanding of the factors diffusing sustainable practices among PSC members. This, in turn, would inform the development of more effective strategies and policies for achieving sustainable SCs across diverse contexts and industries.

Appendix 1

Variable	Type	Equation	Unite
REG	S	$REG_t = REG_{t-1} + DRRE$	Enterprise
REN	S	$REN_t = REN_{t-1} - DRRE$	Enterprise
DG	S	$DG_t = DG_{t-1} + DRD$	Enterprise
DN	S	$DN_t = DN_{t-1} - DRD$	Enterprise
RG	S	$RG_t = RG_{t-1} + DRR$	Enterprise
RN	S	$RN_t = RN_{t-1} - DRR$	Enterprise
POP	S	$POP_t = POP_{t-1} + NPGR$	Million People
DRRE	F	*DRRE*= *IF THEN ELSE*((*TRRE*> 0), (*REN*× *TRRE*), (*REG*× *TRRE*))	Enterprise/Month
DRD	F	*DRD*= *IF THEN ELSE*((*TRD*> 0), (*DN*× *TRD*), (*DG*× *TRD*))	Enterprise/Month
DRR	F	*DRR*= *IF THEN ELSE*((*TRR*> 0), (*RN*× *TRR*), (*RG*× *TRR*))	Enterprise/Month
NPGR	F	$NPGR = POP \times \frac{NNBR}{NBRICCOV}$	Million People/Month
NPDR	F	*NPDR*= *POP*/*LT*	Million People/Month
PDRCOV	F	*PDRCOV*= *POP*× (*COVIR*/100) × (*COVDR*/100)	Million People/Month
RCD, RCR, RCRE	C	–	Dmnl
SDRE, SDD, SDR	C	–	Month
PECDG, PECDN, PECRG, PECRN	C	–	Dmnl
DECDG, DECDN, DRECDG	C	–	TCO2e/Product
JCDG, JCRG	C	–	Employee/(Month*Enterprise)
FEPG, FEPN	C	–	Million US Dollars/Product
FEDG, FEDN, RERDG	C	–	Million US Dollars/TCO2e
RJCG, CREG, CDG, CRG	C	–	Million US Dollars/Employee
NVCDG, NVCRG, GB, PDG, PRG	C	–	Million US Dollars/(Month*Enterprise)
TPDG, TPDN	C	–	Million US Dollars/Product
NNBR	C	–	1/Month
LT	C	–	Month
NCR	C	–	(Product/Month)/Million People
COVNDR	C	–	1/Month

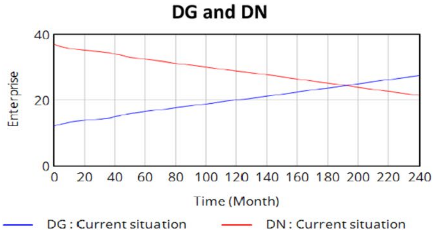
Variable	Type	Equation	Unite
APSPD APSPR NAPSPR	C	–	Million US Dollars/Product
Alpha1, Alpha2, Beta1, Beta2, FCOVIR, FCOVDR, FCOVNBR, FCOVCR	C, LU	–	Dmnl
COVIR	A	*COVIR*= *FCOVIR*(*Time*/*TIME STEP*)	Dmnl
NBRICCOV	A	*NBRICCOV*= *FCOVNBR*(*COVIR*)	Dmnl
COVDR	A	*COVDR*= *FCOVDR*(*Time*/*TIME STEP*) × *COVNDR*	1/Month
CRICCOV	A	*CRICCOV*= *FCOVCR*(*COVIR*)	Dmnl
VCDG	A	*VCDG*= 0.01 × CDG	Million US Dollars/(Month*Enterprise)
VCRG	A	*VCRG*= 0.02 × CRG	Million US Dollars/(Month*Enterprise)
CD	A	*CD*= *POP*× *NCR*× *CRICCOV*× $\left(\frac{VCDG}{NVCDG}\right)^{Beta1} \times \left(\frac{VCRG}{NVCRG}\right)^{Beta2} \times \left(\frac{APSPR}{NAPSPR} \times (1-SRG)\right)^{-Alpha1} \times \left(\frac{APSPR}{NAPSPR}\right)^{-Alpha2}$	Product/Month
TDRG	A	$TDRG = X_{G_3} \times CD$	Product/Month
TDRN	A	*TDRN*= *CD* − *TDRG*	Product/Month
DRGDG	A	$DRGDG = X_{G_2} \times TDRG$	Product/Month
DRGDN	A	*DRGDN*= *TDRG*− *DRGDG*	Product/Month
DRNDG	A	$DRNDG = X_{G_2} \times TDRN$	Product/Month
DRNDN	A	*DRNDN*= *TDRN*− *DRNDG*	Product/Month
TDDG	A	*TDDG*= *DRGDG*+ *DRNDG*	Product/Month
TDDN	A	*TDDN*= *DRGDN*+ *DRNDN*	Product/Month
SDG	A	*SDG*= *IF THEN ELSE*$((X_{G_1} = 0), 0, 0)$	Dmnl
SRG	A	*SRG*= *IF THEN ELSE*$((X_{G_1} = 0), 0, 0)$	Dmnl
ACRG	A	*ACRG*= ((*APSPD*× *DRGDN*) + (*DRGDG*× (1 − *SDG*) × *APSPD*))/ (*DRGDG*+ *DRGDN*)	Million US Dollars/Product
ACRN	A	*ACRN*= ((*APSPD*× *DRNDN*) + (*DRNDG*× (1 − *SDG*) × *APSPD*))/ (*DRNDN*+ *DRNDG*)	Million US Dollars/Product
SPRG	A	*SPRG*= *APSPR*− *ACRG*	Million US Dollars/Product
SPRN	A	*SPRN*= *APSPR*− *ACRN*	Million US Dollars/Product
EMQDG	A	*EMQDG*= *EPPDG*× *TDDG*	Product/Month
EMQDN	A	*EMQDN*= *EPPDN*× *TDDN*	Product/Month
EMQRG	A	*EMQRG*= *EPPRG*× *TDRG*	Product/Month
EMQRN	A	*EMQRN*= *EPPRN*× *TDRN*	Product/Month
TEDG	A	*TEDG*= *DECDG*× *TDDG*	TCO2e/Month
TEDN	A	*TEDN*= *DECDN*× *TDDN*	TCO2e/Month
TREDG	A	*TREDG*= *DRECDG*× *TDDG*	TCO2e/Month
TJCDG	A	*TJCDG*= *DG*× *JCDG*	Employee/Month
TJCRG	A	*TJCRG*= *RG*× *JCRG*	Employee/Month

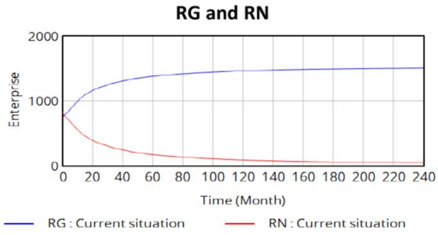
Variable	Type	Equation	Unite
RDG	A	*RDG*= ((*TJCDG*× *RJCG*) + (*TREDG*× *RERDG*))/*DG*	Million US Dollars/(Month*Enterprise)
RRG	A	*RRG*= (*RJCG*× *TJCRG*)/*RG*	Million US Dollars/(Month*Enterprise)
FDG	A	*FDG*= ((*EMQDG*× *FEPG*) + (*TEDG*× *FEDG*))/*DG*	Million US Dollars/(Month*Enterprise)
FDN	A	*FDN*= ((*EMQDN*× *FEPN*) + (*TEDN*× *FEDN*))/*DN*	Million US Dollars/(Month*Enterprise)
FRG	A	*FRG*= (*EMQRG*× *FEPG*)/*RG*	Million US Dollars/(Month*Enterprise)
FRN	A	*FRN*= (*EMQRN*× *FEPN*)/*RN*	Million US Dollars/(Month*Enterprise)
X_{G_1}	A	X_{G1}= *REG*/(*REG*+ *REN*)	Dmnl
X_{N_1}	A	$X_{N1} = 1 - X_{G_1}$	Dmnl
X_{G_2}	A	$X_{G2} = DG/(DG + DN)$	Dmnl
X_{N_2}	A	$X_{N2} = 1 - X_{G_2}$	Dmnl
X_{G_3}	A	$X_{G3} = RG/(RG + RN)$	Dmnl
X_{N_3}	A	$X_{N3} = 1 - X_{G_3}$	Dmnl
U_{G_1}	A	Equation (5)	Million US Dollars/(Month*Enterprise)
U_{G_2}	A	Equation (6)	Million US Dollars/(Month*Enterprise)
U_{G_3}	A	Equation (7)	Million US Dollars/(Month*Enterprise)
U_{N_1}	A	Equation (8)	Million US Dollars/(Month*Enterprise)
U_{N_2}	A	Equation (9)	Million US Dollars/(Month*Enterprise)
U_{N_3}	A	Equation (10)	Million US Dollars/(Month*Enterprise)
$(\#(U_{G_1} - U_{N_1})$ – $\#(U_{N_1} - U_{G_1}))$	A	*IFTHENELSE*($(U_{G_1} - U_{N_1})$ < 0, $(U_{G_1} - U_{N_1})/U_{G_1}$, 0) – *IFTHENELSE*($(U_{N_1} - U_{G_1})$< 0, $(U_{N_1} - U_{G_1})/U_{N_1}$, 0)	Dmnl
$(\#(U_{G_2} - U_{N_2})$ – $\#(U_{N_2} - U_{G_2}))$	A	*IFTHENELSE*($(U_{G_2} - U_{N_2})$ < 0, $(U_{G_2} - U_{N_2})/U_{G_2}$, 0) – *IFTHENELSE*($(U_{N_2} - U_{G_2})$< 0, $(U_{N_2} - U_{G_2})/U_{N_2}$, 0)	Dmnl
$(\#(U_{G_3} - U_{N_3})$ – $\#(U_{N_3} - U_{G_3}))$	A	*IFTHENELSE*($(U_{G_3} - U_{N_3})$< 0, $(U_{G_3} - U_{N_3})/U_{G_3}$, 0)– *IF-THENELSE*($(U_{N_3} - U_{G_3})$< 0, $(U_{N_3} - U_{G_3})/U_{N_3}$, 0)	Dmnl
PI_1	A	P_{IRE}= *RANDOMNORMAL*(0, 1, *RCRE*, 0.1, 0)	1/Month
PI_2	A	P_{ID}= *RANDOMNORMAL*(0, 1, *RCD*, 0.1, 0)	1/Month
PI_3	A	P_{IR}= *RANDOMNORMAL*(0, 1, *RCR*, 0.1, 0)	1/Month
BRRE	A	Equation (2)	Dmnl
BRD	A	Equation (3)	Dmnl
BRR	A	Equation (4)	Dmnl
TRRE	A	*TRRE*= *BRRE*/*SDRE*	1/Month
TRD	A	*TRD*= *BRD*/*SDD*	1/Month
TRR	A	*TRR*= *BRR*/*SDR*	1/Month

S: Stock, F: Flow, A: Auxiliary, C: Constant

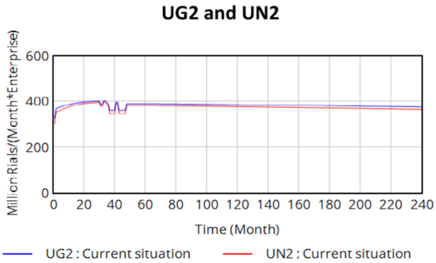
Appendix 2

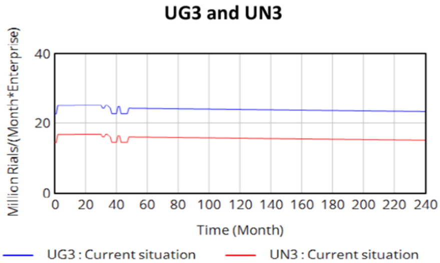
SSCM diffusion



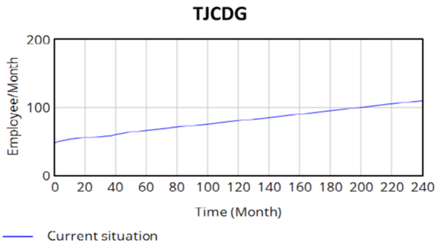


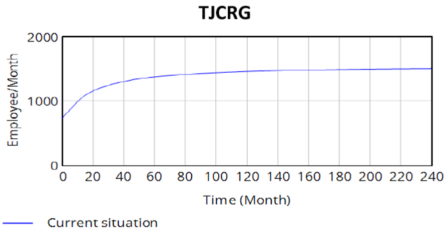
Economic sustainability



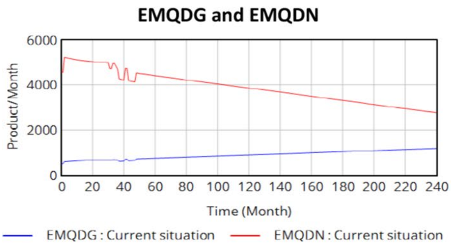


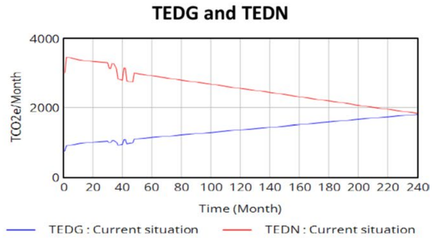
Social sustainability



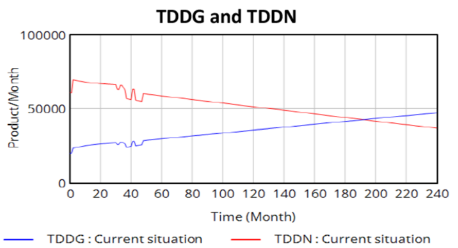


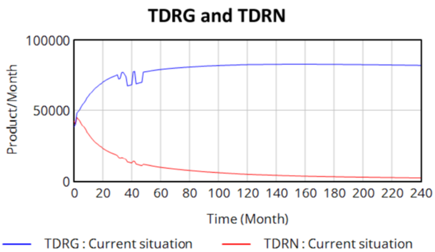
Environmental sustainability





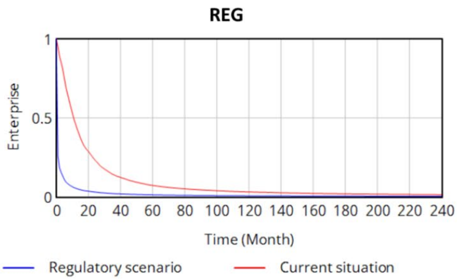
Demand market

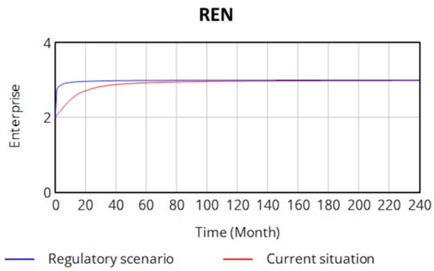




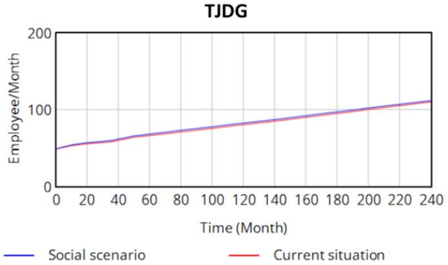
Appendix 3

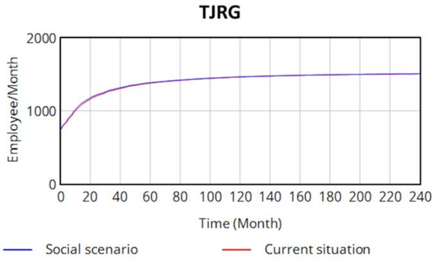
Regulatory scenario



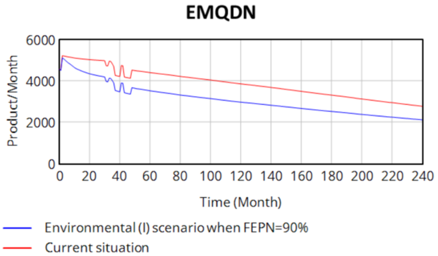


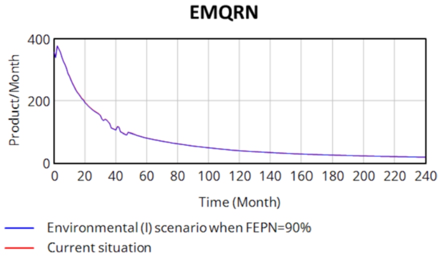
Social scenario



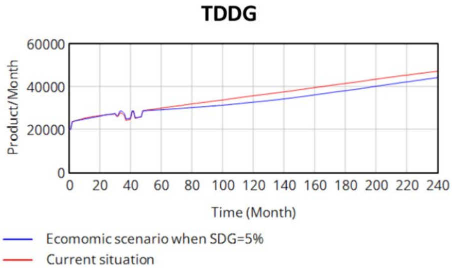


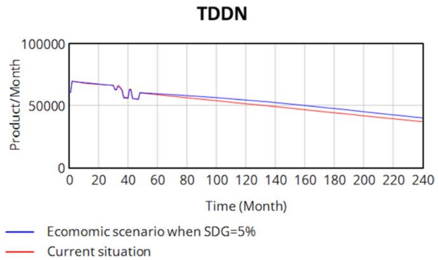
Environmental scenario (I)





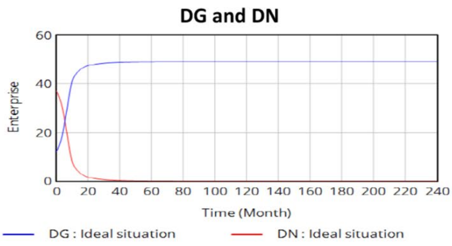
Economic scenario

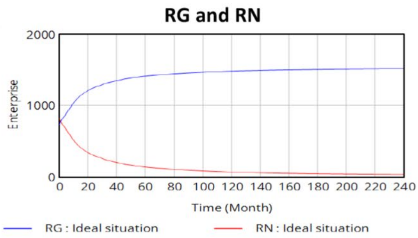




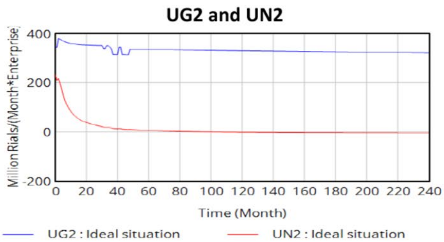
Appendix 4

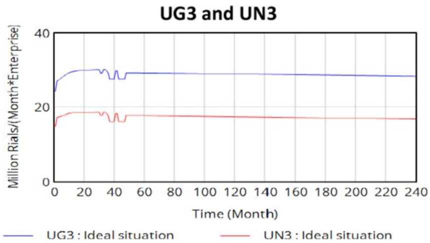
SSCM diffusion



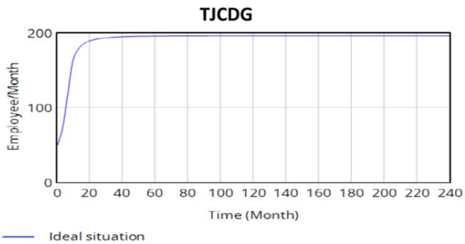


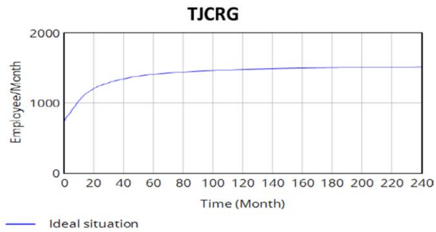
Economic sustainability



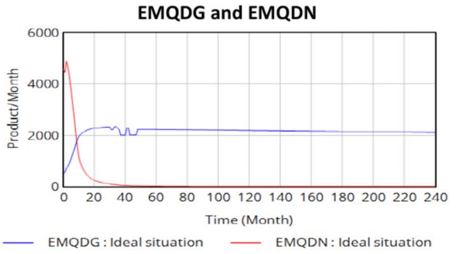


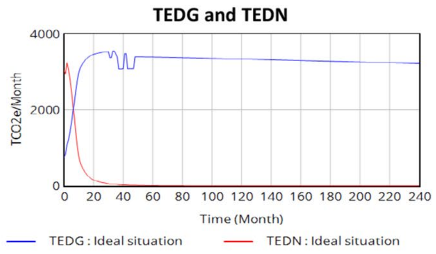
Social sustainability



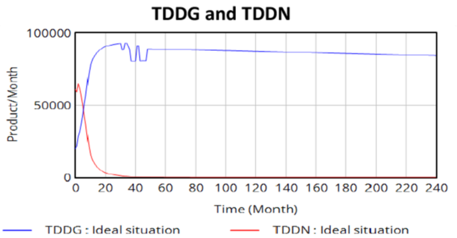


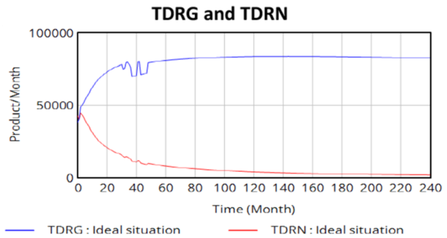
Environmental sustainability





Demand market





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Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval This article contains no studies performed by authors with human participants or animals.

Informed consent Informed consent was obtained from all individual participants in the study, including all experts.

References

Ahi, P., & Searcy, C. (2013). A comparative literature analysis of definitions for green and sustainable supply chain management. *Journal of Cleaner Production,52*, 329–341. https://doi.org/10.1016/j.jclepro.2013.02.018

Ahmad, F., Alnowibet, K. A., Alrasheedi, A. F., & Adhami, A. Y. (2022). A multi-objective model for optimizing the socio-economic performance of a pharmaceutical supply chain. *Socio-Economic Planning Sciences,79*, Article 101126. https://doi.org/10.1016/j.seps.2021.101126

Bade, C., Olsacher, A., Boehme, P., Truebel, H., Bürger, L., & Fehring, L. (2024). Sustainability in the pharmaceutical industry—An assessment of sustainability maturity and effects of sustainability measure implementation on supply chain security. *Corporate Social Responsibility and Environmental Management,31*(1), 224–242. https://doi.org/10.1002/csr.2564

Bai, R., & Zhang, M. (2018). An art district system dynamics model of diversified operation based on game theory. *Journal of Discrete Mathematical Sciences and Cryptography,21*(4), 1019–1030. https://doi.org/10.1080/09720529.2018.1479178

Belkhir, L., & Elmeligi, A. (2019). Carbon footprint of the global pharmaceutical industry and relative impact of its major players. *Journal of Cleaner Production,214*, 185–194. https://doi.org/10.1016/j.jclepro.2018.11.204

Bravo, A., & Carvalho, J. (2015). Challenging times to pharmaceutical supply chains towards sustainability: A case study application. *International Journal of Procurement Management,8*(1–2), 126–140. https://doi.org/10.1504/IJPM.2015.066292

Campos, E., Paula, I., Pagani, R., & Guarnieri, P. (2017). Reverse logistics for the end-of-life and end-of-use products in the pharmaceutical industry: A systematic literature review. *Supply Chain Management,22*(4), 375–392. https://doi.org/10.1108/SCM-01-2017-0040

Chaturvedi, U., Sharma, M., Dangayach, G., & Sarkar, P. (2017). Evolution and adoption of sustainable practices in the pharmaceutical industry: An overview with an Indian Perspective. *Journal of Cleaner Production,168*, 1358–1369. https://doi.org/10.1016/j.jclepro.2017.08.184

Chen, J., Qi, T., Liu, L., Ling, Y., Qian, Z., Li, T., & Zhang, Y. (2020). Clinical progression of patients with COVID-19 in Shanghai. *China. Journal of Infection,80*(5), e1–e6. https://doi.org/10.1016/j.jinf.2020.03.004

Cobb, C. W., & Douglas, P. H. (1928). A theory of production. *The American Economic Review,18*(1), 139–165.

Diewert, W. E., & Wales, T. J. (1987). Flexible functional forms and global curvature conditions. *Econometrica,55*(1), 43–68. https://doi.org/10.2307/1911156

Duan, W., Li, C., Zhang, P., & Chang, Q. (2016). Game modelling and policy research on the system dynamics-based tripartite evolution for government environmental regulation. *Cluster Computing,19*(4), 2061–2074. https://doi.org/10.1007/s10586-016-0642-1

EFPIA. (2023). *The Pharmaceutical Industry in Figures*. EFPIA (The European Federation of Pharmaceutical Industries and Associations). https://www.efpia.eu/media/rm4kzdlx/the-pharmaceutical-industry-in-figures-2023.pdf

Eghbali, M. A., Rasti-Barzoki, M., & Safarzadeh, S. (2022). A hybrid evolutionary game-theoretic and system dynamics approach for analysis of implementation strategies of green technological innovation under government intervention. *Technology in Society,70*, Article 102039. https://doi.org/10.1016/j.techsoc.2022.102039

Feng, F., Liu, C., & Zhang, J. (2020). China's railway transportation safety regulation system based on evolutionary game theory and system dynamics. *Risk Analysis,40*(10), 1944–1966. https://doi.org/10.1111/risa.13528

Goodarzian, F., Abraham, A., Muñuzuri, J., Taghipour, A., & Ghasemi, P. (2024). A Benders decomposition approach for a new sustainable pharmaceutical supply chain network: A case study in France. *Annals of Operations Research,2024*, 1–39. https://doi.org/10.1007/s10479-024-05936-3

Goodarzian, F., Taleizadeh, A., Ghasemi, P., & Abraham, A. (2021). An integrated sustainable medical supply chain network during COVID-19. *Engineering Applications of Artificial Intelligence,100*, Article 104188. https://doi.org/10.1016/j.engappai.2021.104188

Guo, J., Zhong, M., & Chen, S. (2022). Analysis and simulation of BECCS vertical integration model in China based on evolutionary game and system dynamics. *Energy,252*, Article 124000. https://doi.org/10.1016/j.energy.2022.124000

Guo, S. (2023). Tackling China's local environmental policy implementation gap: An evolutionary game analysis of China's environmental protection inspection system. *Journal of Cleaner Production,416*, Article 137942. https://doi.org/10.1016/j.jclepro.2023.137942

Halim, I., Ang, P., & Adhitya, A. (2019). A decision support framework and system for design of sustainable pharmaceutical supply chain network. *Clean Technologies and Environmental Policy,21*, 431–446. https://doi.org/10.1007/s10098-018-1646-8

Han, R., & Yang, M. (2022). Profit distribution and stability analysis of joint distribution alliance based on tripartite evolutionary game theory under the background of green and low carbon. *Environmental Science and Pollution Research,29*(39), 59633–59652. https://doi.org/10.1007/s11356-022-19712-y

Hosseini-Motlagh, S. M., Jazinaninejad, M., & Nami, N. (2022). Coordinating a socially concerned reverse supply chain for pharmaceutical waste management considering government role. *Environment, Development and Sustainability,2022*, 1–26. https://doi.org/10.1007/s10668-021-01511-z

Janatyan, N., Zandieh, M., Alem-Tabriz, A., & Rabieh, M. (2021). A robust optimisation model for sustainable pharmaceutical distribution network design: A case study. *Annals of Operations Research,2021*, 1–20. https://doi.org/10.1007/s10479-020-03900-5

Jiang, Z.-Z., He, N., Qin, X., Ip, W., Wu, C., & Yung, K. (2018). Evolutionary game analysis and regulatory strategies for online group-buying based on system dynamics. *Enterprise Information Systems,12*(6), 695–713. https://doi.org/10.1080/17517575.2017.1412503

Kim, D.-H., & Kim, D. (1997). A system dynamics model for a mixed-strategy game between police and driver. *System Dynamics Review,13*(1), 33–52. https://doi.org/10.1002/(SICI)1099-1727(199721)13:1%3cC33::AID-SDR114%3e3.0.CO;2-Y

Kumar, A., Zavadskas, E., Mangla, S., Agrawal, V., Sharma, K., & Gupta, D. (2019). When risks need attention: Adoption of green supply chain initiatives in the pharmaceutical industry. *International Journal of Production Research,57*(11), 3554–3576. https://doi.org/10.1080/00207543.2018.1543969

Li, K., Zhang, Y., Guo, J., Ge, X., & Su, Y. (2019). System dynamics model for high-speed railway operation safety supervision system based on evolutionary game theory. *Concurrency and Computation: Practice and Experience,31*(10), Article e4743. https://doi.org/10.1002/cpe.4743

Li, Y., Yang, T., & Zhang, Y. (2022). Evolutionary game theory-based system dynamics modeling for community solid waste classification in China. *Utilities Policy,79*, Article 101451. https://doi.org/10.1016/j.jup.2022.101451

Liu, Q., Li, X., & Hassall, M. (2015). Evolutionary game analysis and stability control scenarios of coal mine safety inspection system in China based on system dynamics. *Safety Science,80*, 13–22. https://doi.org/10.1016/j.ssci.2015.07.005

Liu, W., & Li, Y. (2023). Four-party evolutionary game analysis of third-party recycling treatment of livestock and poultry breeding waste. *Journal of Cleaner Production,415*, Article 137829. https://doi.org/10.1016/j.jclepro.2023.137829

Liu, W., Wan, Z., Wan, Z., & Gong, B. (2020). Sustainable recycle network of heterogeneous pharmaceuticals with governmental subsidies and service-levels of third-party logistics by bi-level programming approach. *Journal of Cleaner Production,249*, Article 119324. https://doi.org/10.1016/j.jclepro.2019.119324

Lotfi, A., Shakouri, M., Abazari, S. R., Aghsami, A., & Rabbani, M. (2023). A multi-objective optimization for a closed-loop sustainable pharmaceutical supply chain network design: A case study. *Journal of Advances in Management Research,20*(4), 565–598. https://doi.org/10.1108/JAMR-05-2022-0100

Low, Y., Halim, I., Adhitya, A., Chew, W., & Sharratt, P. (2016). Systematic Framework for Design of Environmentally Sustainable Pharmaceutical Supply Chain Network. *Journal of Pharmaceutical Innovation,11*, 250–263. https://doi.org/10.1007/s12247-016-9255-8

Luthra, S., Kumar, A., Zavadskas, E. K., Mangla, S. K., & Garza-Reyes, J. A. (2020). Industry 4.0 as an enabler of sustainability diffusion in supply chain: An analysis of influential strength of drivers in an emerging economy. *International Journal of Production Research,58*(5), 1505–1521. https://doi.org/10.1080/00207543.2019.1660828

Ma, L., & Hu, J. (2018). An analysis of the eco-innovation mechanism and policies in the pulp and paper industry based on coupled game theory and system dynamics. *Sustainability-Basel,10*(10), 3482. https://doi.org/10.3390/su10103482

Mahdiraji, H. A., Govindan, K., Madadi, S., & Arturo Garza-Reyes, J. (2022a). Coordination in a closed-loop sustainable supply chain considering dual-channel and cost-sharing contract: Evidence from an emerging economy. *Journal of the Operational Research Society,74*(11), 1–20. https://doi.org/10.1080/01605682.2022.2147032

Mahdiraji, H. A., Hatami-Marbini, A., Moazed, N. M., Ansari, M., & Kamardi, A. A. A. (2021). Differential game approach to pricing and advertising decisions. *Operations Research Letters,49*(5), 688–695. https://doi.org/10.1016/j.orl.2021.07.002

Mahdiraji, H. A., Yaftiyan, F., Abbasi-Kamardi, A., & Garza-Reyes, J. A. (2022b). Investigating potential interventions on disruptive impacts of Industry 4.0 technologies in circular supply chains: Evidence from SMEs of an emerging economy. *Computers & Industrial Engineering,174*, 108753. https://doi.org/10.1016/j.cie.2022.108753

Malleeswaran, B., & Uthayakumar, R. (2022). A sustainable pharmaceutical supply chain model for household energy consumption and expiration cost under decision making approach. *Cleaner Engineering and Technology,11*, Article 100568. https://doi.org/10.1016/j.clet.2022.100568

Meqdadi, O. A., Johnsen, T. E., & Johnsen, R. E. (2019). Power and diffusion of sustainability in supply networks: Findings from four in-depth case studies. *Journal of Business Ethics,159*, 1089–1110. https://doi.org/10.1007/s10551-018-3835-0

Milanesi, M., Runfola, A., & Guercini, S. (2020). Pharmaceutical industry riding the wave of sustainability: Review and opportunities for future research. *Journal of Cleaner Production,261*, Article 121204. https://doi.org/10.1016/j.jclepro.2020.121204

Moosivand, A., Rangchian, M., Zarei, L., Peiravian, F., Mehralian, G., & Sharifnia, H. (2021). An application of multi-criteria decision making approach to sustainable drug shortages management: Evidence from a developing country. *Journal of Pharmaceutical Health Care and Sciences,7*(14), 1–11. https://doi.org/10.1186/s40780-021-00200-3

Nematollahi, M., Hosseini-Motlagh, S.-M., Ignatius, J., Goh, M., & Saghafi Nia, M. (2018). Coordinating a socially responsible pharmaceutical supply chain under periodic review replenishment policies. *Journal of Cleaner Production,172*, 2876–2891. https://doi.org/10.1016/j.jclepro.2017.11.126

Nie, S., Cai, G., Huang, Y., & He, J. (2024). Deciphering stakeholder strategies in electric vehicle battery recycling: Insights from a tripartite evolutionary game and system dynamics. *Journal of Cleaner Production,452*, Article 142174. https://doi.org/10.1016/j.jclepro.2024.142174

Pan, H., Yang, B., Pan, Y., & Luo, Z. (2024). Evolutionary game of incentive strategy for Chinese prefabricated buildings based on system dynamics from the perspective of prospect theory. *Engineering, Construction and Architectural Management.*https://doi.org/10.1108/ECAM-10-2023-1031

Paul, J., Lim, W. M., O'Cass, A., Hao, A. W., & Bresciani, S. (2021). Scientific procedures and rationales for systematic literature reviews (SPAR-4-SLR). *International Journal of Consumer Studies,45*(4), O1–O16. https://doi.org/10.1111/ijcs.12695

Pesqueira, A., Sousa, M., & Rocha, Á. (2020). Big data skills sustainable development in healthcare and pharmaceuticals. *Journal of Medical Systems,44*(197), 1–15. https://doi.org/10.1007/s10916-020-01665-9

Pimenta, H. C. D., Ball, P., & Salonitis, K. (2021). Supply chain environmental and social sustainability practice diffusion: Bibliometrics, content analysis and conceptual framework. *Corporate Social Responsibility and Environmental Management,28*(6), 1870–1890. https://doi.org/10.1002/csr.2165

Qiu, Y., Shi, M., Zhao, X., & Jing, Y. (2021). System dynamics mechanism of cross-regional collaborative dispatch of emergency supplies based on multi-agent game. *Complex & Intelligent Systems,9*, 2321–2332. https://doi.org/10.1007/s40747-021-00303-2

Rebs, T., Brandenburg, M., & Seuring, S. (2019). System dynamics modeling for sustainable supply chain management: A literature review and systems thinking approach. *Journal of Cleaner Production,208*, 1265–1280. https://doi.org/10.1016/j.jclepro.2018.10.100

Rekabi, S., Goodarzian, F., Garjan, H. S., Zare, F., Muñuzuri, J., & Ali, I. (2023). A data-driven mathematical model to design a responsive-sustainable pharmaceutical supply chain network: A Benders decomposition approach. *Annals of Operations Research,2023*, 1–42. https://doi.org/10.1007/s10479-023-05734-3

Reynés, F. (2019). The Cobb-Douglas function as a flexible function: A new perspective on homogeneous functions through the lens of output elasticities. *Mathematical Social Sciences,97*, 11–17. https://doi.org/10.1016/j.mathsocsci.2018.10.002

Romdhani, S., Nouaouri, I., Tounsi, J., Gattoufi, S., & Allaoui, H. (2022). Two-echelon Inventory Management for Sustainable Pharmaceutical Supply Chain through Waste Reduction. *IFAC-PapersOnLine,55*(10), 1380–1385. https://doi.org/10.1016/j.ifacol.2022.09.583

Roshan, M., Tavakkoli-Moghaddam, R., & Rahimi, Y. (2019). A two-stage approach to agile pharmaceutical supply chain management with product substitutability in crises. *Computers & Chemical Engineering,127*, 200–217. https://doi.org/10.1016/j.compchemeng.2019.05.014

Sazvar, Z., Zokaee, M., Tavakkoli-Moghaddam, R., Salari, S.-S., & Nayeri, S. (2021). Designing a sustainable closed-loop pharmaceutical supply chain in a competitive market considering demand uncertainty, manufacturer's brand and waste management. *Annals of Operations Research,315*, 2057–2088. https://doi.org/10.1007/s10479-021-03961-0

Sazvar, Z., Zokaee, M., Tavakkoli-Moghaddam, R., Salari, S. A. S., & Nayeri, S. (2022). Designing a sustainable closed-loop pharmaceutical supply chain in a competitive market considering demand uncertainty, manufacturer's brand and waste management. *Annals of Operations Research,2022*, 1–32. https://doi.org/10.1007/s10479-021-03961-0

Shamsuzzoha, A., Ndzibah, E., & Kettunen, K. (2020). Data-driven sustainable supply chain through centralised logistics network: Case study in a Finnish pharmaceutical distributor company. *Current Research in Environmental Sustainability,2*, Article 100013. https://doi.org/10.1016/j.crsust.2020.100013

Shan, S. N., Zhang, Z. C., Ji, W. Y., & Wang, H. (2023). Analysis of collaborative urban public crisis governance in complex system: A multi-agent stochastic evolutionary game approach. *Sustainable Cities and Society,91*, Article 104418. https://doi.org/10.1016/j.scs.2023.104418

Shekoohi Tolgari, F., & Zarrinpoor, N. (2024). A robust reverse pharmaceutical supply chain design considering perishability and sustainable development objectives. *Annals of Operations Research,2024*, 1–53. https://doi.org/10.1007/s10479-024-05871-3

Sheng, J., Tang, L., Yang, Z., Yu, M., & Liu, X. (2023). Strategies of stakeholders' selection of shore-to-ship power in China. *Transportation Research Part D: Transport and Environment,119*, Article 103729. https://doi.org/10.1016/j.trd.2023.103729

Shi, W., Wang, H., Chen, C., & Kong, Z. (2021). Evolutionary game analysis of decision-making dynamics of local governments and residents during wildfires. *International Journal of Disaster Risk Reduction,53*, Article 101991. https://doi.org/10.1016/j.ijdrr.2020.101991

Shokouhyar, S., Seddigh, M., & Panahifar, F. (2020). Impact of big data analytics capabilities on supply chain sustainability: A case study of Iran. *World Journal of Science, Technology and Sustainable Development,17*(1), 33–57. https://doi.org/10.1108/WJSTSD-06-2019-0031

Singh, A. K., & Mukherjee, K. (2022). A penalty-reward system for pro-environmental project execution. *Applied Economics Letters,29*(6), 477–483. https://doi.org/10.1080/13504851.2020.1870918

Song, X., Ge, Z., Zhang, W., Wang, Z., Huang, Y., & Liu, H. (2023). Study on multi-subject behavior game of CCUS cooperative alliance. *Energy,262*, Article 125229. https://doi.org/10.1016/j.energy.2022.125229

Sterman, J. (2000). *Systems thinking and modeling for a complex world*. Working Paper ESD-WP-2003-01.13, MIT Sloane School of Management. http://hdl.handle.net/1721.1/102741

Tavana, M., Amoozad Mahdiraji, H., Beheshti, M., & Abbasi Kamardi, A. A. (2020). Optimal strategic alliance in multi-echelon supply chains with open innovation. *Managerial and Decision Economics,41*(7), 1365–1384. https://doi.org/10.1002/mde.3181

Tian, Y., Govindan, K., & Zhu, Q. (2014). A system dynamics model based on evolutionary game theory for green supply chain management diffusion among Chinese manufacturers. *Journal of Cleaner Production,80*, 96–105. https://doi.org/10.1016/j.jclepro.2014.05.076

Tsolakis, N., & Srai, J. (2018). Mapping supply dynamics in renewable feedstock enabled industries: A systems theory perspective on "green" pharmaceuticals. *Operations Management Research,11*, 83–104. https://doi.org/10.1007/s12063-018-0134-y

Viegas, C., Bond, A., Vaz, C., & JoãoBertolo, R. (2019). Reverse flows within the pharmaceutical supply chain: A classificatory review from the perspective of end-of-use and end-of-life medicines. *Journal of Cleaner Production,238*, Article 117719. https://doi.org/10.1016/j.jclepro.2019.117719

Wang, M., Li, Y., Cheng, Z., Zhong, C., & Ma, W. (2021b). Evolution and equilibrium of a green technological innovation system: Simulation of a tripartite game model. *Journal of Cleaner Production,278*, Article 123944. https://doi.org/10.1016/j.jclepro.2020.123944

Wang, W., Feng, L., Zheng, T., & Liu, Y. (2021a). The sustainability of ecotourism stakeholders in ecologically fragile areas: Implications for cleaner production. *Journal of Cleaner Production,279*, Article 123606. https://doi.org/10.1016/j.jclepro.2020.123606

Weraikat, D., Zanjani, M., & Lehoux, N. (2016a). Coordinating a green reverse supply chain in pharmaceutical sector by negotiation. *Computers & Industrial Engineering,93*, 67–77. https://doi.org/10.1016/j.cie.2015.12.026

Weraikat, D., Zanjani, M., & Lehoux, N. (2016b). Two-echelon pharmaceutical reverse supply chain coordination with customers incentives. *International Journal of Production Economics,176*, 41–52. https://doi.org/10.1016/j.ijpe.2016.03.003

Weraikat, D., Zanjani, M., & Lehoux, N. (2019). Improving sustainability in a two-level pharmaceutical supply chain through Vendor-Managed Inventory system. *Operations Research for Health Care,21*, 44–55. https://doi.org/10.1016/j.orhc.2019.04.004

You, M., Li, S., Li, D., Cao, Q., & Xu, F. (2020). Evolutionary game analysis of coal-mine enterprise internal safety inspection system in China based on system dynamics. *Resources Policy,67*, Article 101673. https://doi.org/10.1016/j.resourpol.2020.101673

Yu, X., Ge, S., Zhou, D., Wang, Q., Chang, C. T., & Sang, X. (2022). Whether feed-in tariff can be effectively replaced or not? An integrated analysis of renewable portfolio standards and green certificate trading. *Energy,245*, Article 123241. https://doi.org/10.1016/j.energy.2022.123241

Yuan, L., He, W., Degefu, D., Liao, Z., Wu, X., An, M., & Ramseya, T. (2020). Transboundary water sharing problem; a theoretical analysis using evolutionary game and system dynamics. *Journal of Hydrology,582*, 124521. https://doi.org/10.1016/j.jhydrol.2019.124521

Zahiri, B., Jula, P., & Tavakkoli-Moghaddam, R. (2018). Design of a pharmaceutical supply chain network under uncertainty considering perishability and substitutability of products. *Information Sciences,423*, 257–283. https://doi.org/10.1016/j.ins.2017.09.046

Zahiri, B., Zhuang, J., & Mohammadi, M. (2017). Toward an integrated sustainable-resilient supply chain: A pharmaceutical case study. *Transportation Research Part E,103*, 109–142. https://doi.org/10.1016/j.tre.2017.04.009

Zandkarimkhani, S., Mina, H., Biuki, M., & Govindan, K. (2020). A chance constrained fuzzy goal programming approach for perishable pharmaceutical supply chain network design. *Annals of Operations Research,295*, 425–452. https://doi.org/10.1007/s10479-020-03677-7

Zhang, C. (2016). Small and medium-sized enterprises closed-loop supply chain finance risk based on evolutionary game theory and system dynamics. *Journal of Shanghai Jiaotong University (Science),21*, 355–364. https://doi.org/10.1007/s12204-016-1733-0

Zhang, S., Wang, C., & Yu, C. (2019). The evolutionary game analysis and simulation with system dynamics of manufacturer's emissions abatement behavior under cap-and-trade regulation. *Applied Mathematics and Computation,355*, 343–355. https://doi.org/10.1016/j.amc.2019.02.080

Zhao, R., Zhou, X., Han, J., & Liu, C. (2016). For the sustainable performance of the carbon reduction labeling policies under an evolutionary game simulation. *Technological Forecasting & Social Change,112*, 262–274. https://doi.org/10.1016/j.techfore.2016.03.008

Zhao, X., Ma, X., Chen, B., Shang, Y., & Song, M. (2022). Challenges toward carbon neutrality in China: Strategies and countermeasures. *Resources, Conservation and Recycling,176*, Article 105959. https://doi.org/10.1016/j.resconrec.2021.105959

Zhou, X., Zhao, R., Cheng, L., & Min, X. (2019). Impact of policy incentives on electric vehicles development: A system dynamics-based evolutionary game theoretical analysis. *Clean Technologies and Environmental Policy,21*, 1039–1053. https://doi.org/10.1007/s10098-019-01691-3

Zhu, C., Fan, R., & Lin, J. (2020). The impact of renewable portfolio standard on retail electricity market: A system dynamics model of tripartite evolutionary game. *Energy Policy,136*, Article 111072. https://doi.org/10.1016/j.enpol.2019.111072

Zhu, Q., Shah, P., & Sarkis, J. (2018). Addition by subtraction: Integrating product deletion with lean and sustainable supply chain management. *International Journal of Production Economics,205*, 201–214. https://doi.org/10.1016/j.ijpe.2018.08.035

Zuo, W., Qiu, X., Li, S., & He, X. (2023). Online ride-hailing regulation: A simulation study based on evolutionary game theory. *Transportation Planning and Technology,46*(4), 437–461. https://doi.org/10.1080/03081060.2023.2205399

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