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A multi-staged triple bottom line framework and scenarios to improve sustainability of rice supply chains

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Abstract

Purpose – The study aims to propose an approach to improving the sustainability of the rice supply chain (RSC). It is motivated by the challenges related to increased populations and the need to produce more to attain global Sustainable Development Goal (SDG) 2 of zero hunger while still balancing the need for global SDG 15.1 of net zero land degradation and SDG 6.4 of increased water use efficiency.

Design/methodology/approach – The work proposes a three-phased approach to improve the sustainability of the RSC, integrating the social, economic and environmental dimensions of the triple bottom line (TBL). Parameters concerning the sustainability of RSC were ranked using the analytical hierarchy process. A hierarchical model was developed using interpretive structural modeling (ISM). Subsequently, a stock and flow model of the sustainable RSC was modeled using the system dynamics approach to study the changes in farmland area and land usage for various interventions.

Findings – AHP and ISM revealed that farmland area and production rate were the most important parameters. Offering subsidies to farmers, modernizing irrigation and imposing strict regulations produced favorable results in optimizing the RSC and improving sustainability.

Research limitations/implications – Given this study's focus on India, the study parameters could change based on the crop type and geographical location but can be duplicated for other regions/crops. The research has implications for regulators and policymakers in devising suitable real-time strategies and interventions for RSC sustainability, focusing on the nature of operations and interaction among the entities.

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Originality/value – This work is the first to focus on the TBL model integrated for sustainability within the RSC and proposes four interventions targeted towards meeting SDGs.

Keywords Sustainability, Triple bottom line, Rice supply chain, Interpretive structural modeling, System dynamics

Paper type Research paper

1. Introduction

The word “paddy” or “paddy fields” is derived from the Malaysian word for rice plants, which are tropical crops mainly cultivated in several countries. India’s hot and humid climate provides an ideal setting for growing tropical plants like rice throughout where the mean temperature is favorable for rice cultivation throughout the year. India’s rice acreage has recently peaked due to new plant varieties and improved agronomic methods (OECD/ICRIER, 2018). However, India’s total rice yields are still significantly below the global average, with considerable disparities in productivity as compared to other major rice-producing nations (Economic Times, 2016). Technological obsolescence, production and distribution issues, or the limited availability of natural resources such as land and water can lead to productivity issues. All these factors as vital to the rice supply chain (RSC) help explain why agricultural land availability is shrinking and why extending irrigation infrastructure and new technologies is important to rice yield (Hinz *et al.*, 2020).

A key reason as to why agriculture is failing in India is due to the depletion of water supplies and water mismanagement. Urbanization and development have burdened farmers by curtailing the growth of the agricultural industry (Bastan *et al.*, 2017). Changes in living standards and technology, as well as market pressures and urban expansion, have all played vital roles in the decline of agriculture (Mirkatouli *et al.*, 2012). Studies have shown that a methodical approach using the key drivers of food loss and waste in supply chains could improve performance and sustainability and that resilience and responsiveness have been optimized using a robust fuzzy stochastic model (Sharifi *et al.*, 2024). The Triple Bottom Line (TBL) is adopted as an overarching framework that covers economic, social, and environmental dimensions. However, Sustainable Development Goal (SDG) targets aligned across the TBL aid in specific action-outcome mapping.

Food production needs to increase to cater to 1.6 billion people, the projected population of India by 2050 (United Nations, 2017). This need is aligned with SDG 2, which focuses on “Zero Hunger”, specifically SDG 2.4.1. that measures the “Proportion of agricultural area under productive and sustainable agriculture” and SDG 6.4, associated with water use efficiency. Increasing food production is interconnected with several SDG’s that impact the environment and requires a holistic approach. Hence, a systems thinking approach was applied to model interactions between agriculture, urbanization, and the ecosystem. This approach has aided the framing of the research questions to encompass the themes addressing the needs of growing populations (SDG 2.4.1) through the efficient use of water (SDG 6.4) to maintain zero net land degradation (SDG 15). Also, to strengthen the validity of the influence of factors, a three-staged approach was applied. A synergic approach between SDG targets and TBL helps track the improvements in TBL dimensions in light of specific SDG targets over the sustainable long term:

(1) How can we enhance the large-scale, long-term sustainability of RSC?

(2) How do the specific SDG targets illustrate each TBL dimension within the RSC?

The remainder of the manuscript is organized as follows. The literature review is presented in section two. Section three discusses the research methodology including analytical hierarchy process (AHP) used to rank the identified parameters, interpretive structural modeling (ISM), and the system dynamics (SD) model developed to analyze the various strategies to promote the sustainability of agriculture. The results and discussion of the simulation have been presented in sections four and five. The contribution of the present work to the existing theory and implications for practice have been presented in section six while section seven concludes the study.

2. Literature review

2.1 Existing works on the rice supply chain

Several parameters influencing both agri-SCs and RSCs are discussed in the literature. An approach utilizing SD was applied to increase farmers' profits and productivity by 7.6 and 1.4% per annum through a bioindustry program and information sharing. The approach allows observing the effects of interventions through internal and external factors that influence the RSC (Suryani *et al.*, 2020). Factors like demand, production, and availability of rice have caused disparities between deficient and excess territories (Alfa and Subagyo, 2018). These disparities could be reduced by eliminating minimum support prices (MSPs) and monopolies to make regions more self-sufficient (Chung, 2018). Rahman *et al.* (2020) determined that the margins received by rice millers and wholesalers are 33 and 29% above the base cost, evidencing their market dominance. The cluster first route and second approach utilize k-means clustering to group rice cultivars based on productivity. Simulating each group within a local allocation model could reduce transportation costs and margins.

The importance of information sharing in a SC was evident from a study of 458 small-scale farmers in Ghana, where the use of mobile phones, farm size, and gender was shown to influence the selling price, quantity, and returns (Abdul-Rahaman and Abdulai, 2020). Smart farming has recently gained interest among researchers due to its proficiency in addressing diverse problems across the SC. However, addressing each SDG as a silo is an inefficient way of developing frameworks and solutions. Hence, parameters influencing large-scale sustainability were chosen (Table 1). The integration of TBL and SDGs into rice supply chains is key to food security and environmental preservation. Recent research has investigated a range of methodologies for improving the sustainability of the industry. Bello and Mbhele (2024) utilized a fuzzy-AHP technique to analyze sustainable rice management practices in Nigeria, emphasizing water consumption and working conditions. Elyasi and Teimoury (2023) created a Critical Systems Practice model for Iran's RSC, suggesting seven policies to attain sustainability. Singh and Srivastava (2022) developed a decision support system for incorporating TBL sustainability elements into agricultural SC's, determining critical enablers and their interactions. These works emphasize stakeholder involvement, innovative policies, and integrated strategies to attain suscironmental dimensions.

Understanding the parameters' impact on the various SDGs is important, but it is equally important to understand their association with the TBL dimensions (Table 2).

The Tables show that each parameter chosen focuses on one or more SDG targets that address issues across multiple dimensions of TBL (Table 2). Table 1 highlights the measurable global targets, thereby ensuring the assessment's robustness and specificity.

2.2 System Dynamics approach

Evidence-based decision-making is essential in critical application areas where large-scale policy implementations are required (Karthick *et al.*, 2023). Simulation is an effective tool that can help businesses explore various decision options to determine the most feasible and effective ones. The simulation technique provides a risk-free environment by eliminating the need for capital, time, and cost.

The system to be modeled in the present study involves dynamic interactions, feedback effects, and the evolution of the nature of parameters over time (Rich *et al.*, 2018). Also, time-space effects to be analyzed can be effectively handled by SD. These models can outperform quantitative models, especially in spatial and land-use studies (Rich *et al.*, 2018). Their vast application in value chains attracted researchers to investigate the operationalization

Table 1. Parameters and their target SDGs

Parameter	Relevant SDG(s)	Specific SDG goals and targets	References
Commercial land areas owned by multinational corporations (MNCs) or individuals for residential development significantly contribute to understanding how land acquisitions and exploitation negatively impact agriculture	SDG 11: Sustainable Cities and Communities SDG 15: Life on Land	Target 11.3: Enhance inclusive and sustainable urbanization Target 15.3: Combat desertification and restore degraded land	Bastan *et al.* (2017)
Farming turnover explains the economic value of harvest based on the profit generated. It is influenced by the total area of land used for rice cultivation and the efficiency of farming practices	SDG 2: Zero Hunger SDG 8: Decent Work and Economic Growth	Target 2.3: Double agricultural productivity and incomes of small-scale farmers Target 8.2: Promote high levels of economic productivity	Jifroudi *et al.* (2020), Khandelwal *et al.* (2021)
Demand and affordability greatly impact agricultural land availability. As demand influences land prices, this parameter is crucial for analyzing its effect	SDG 2: Zero Hunger SDG 15: Life on Land	Target 2.3: Secure land availability for sustainable food production Target 15.3: Restore degraded land and achieve land degradation neutrality	Khandelwal *et al.* (2021)
Affordability and the cost of acquiring land required for cultivation are key factors in determining agricultural output. Higher costs per hectare result in reduced land being used for farming	SDG 8: Decent Work and Economic Growth SDG 2: Zero Hunger SDG 1: No Poverty	Target 8.10: Enhance access to financial services Target 2.3: Increase in agricultural incomes by improving affordability Target 1.4: Equal access to resources like land	Bastan *et al.* (2017), Khandelwal *et al.* (2021)
The per capita consumption of water affects its availability for farming. An increase in the former reduces the latter proportionately. Population growth determines water consumption and demand for residential or commercial lands	SDG 6: Clean Water and Sanitation SDG 12: Responsible Consumption and Production	Target 6.4: Substantially increase water-use efficiency Target 12.2: Sustainable management of natural resources	
Agricultural resources are limited due to the growing demands of an expanding population. The efficiency of any SC is dependent on two main factors: production rate and overall profit. Researchers have become interested in these factors and have analyzed them using various tools and simulation methods	SDG 2: Zero Hunger SDG 11: Sustainable Cities and Communities	Target 2.1: End hunger and ensure food access Target 11.3: Manage urbanization to reduce resource strain	Food and Agricultural Organisation (2017)
Rainfall is a critical factor impacting agricultural activities in countries like India, where approximately 60% of farmland relies on monsoon rains	SDG 13: Climate Action SDG 2: Zero Hunger	Target 13.1: Strengthen resilience to climate-related hazards Target 2.4: Ensure resilient agricultural practices that improve yield	Zhao *et al.* (2024)

(*continued*)

Table 1. Continued

Parameter	Relevant SDG(s)	Specific SDG goals and targets	References
Water usage is primarily concentrated in agriculture and industry. Maintaining a balance between these two areas is crucial to avoid shortages, making this an essential factor in analyzing agricultural SC's	SDG 6: Clean Water and Sanitation SDG 12: Responsible Consumption and Production	Target 6.4: Increase water-use efficiency and sustainability Target 12.4: Sustainable water resource management to prevent shortages	Kafi *et al.* (2023)

Source(s): Authors' own work

Table 2. Effect of parameters of the dimensions of TBL

Parameter	Description
Commercial land (1)	Social and economic – land exploitation creates a socioeconomic imbalance, widening the socioeconomic gap and affecting the lifestyle of people with low incomes Environmental: This contributes to an increase in temperature by reducing the forest area (deforestation), which contributes to global warming
Farming Turnover (2)	Economic: It governs farmers' profitability and determines their livelihood; agriculture holds a major share in India's Gross Domestic Product (GDP)
Farmland Area (3)	Social—determines the volume of produce required to cater to the growing population. This addresses SDG 2 (zero hunger) Environmental: Improper use of farmland leads to degradation and, thus, conversion for other purposes. It addresses SDG 15 (Net zero land degradation)
Land demand (4)	Economic – depends on the geographical location, urbanization, and other factors determining how the land needs to be used – a trade-off between farming, residing, industrial purposes, and others
Land price (5)	Economic – is a factor that depends on the factors mentioned for Land demand
Per Capita water (6)	Environmental – efficient use of available fresh water is essential Economics requires investment in modern irrigation technologies. It could result in more profit
Population (7)	Social – The increasing population demands more production to cater for needs Environmental – Housing a larger population also requires the conversion of lands to residents and other allied spaces
Production rate (8)	Environmental—There must be increased trading off intensification and geographical expansion. The former increases carbon stocks while decreasing them (Hinz *et al.*, 2020)
Rainfall (9)	Social: It determines crop yield. Human activities, such as deforestation and emissions, disturb it Environment – results in climate change and alteration in soil properties
Water consumption (10)	Environmental and Social– efficient water management could balance freshwater availability for all industrial and residential activities
Water level (11)	Environmental – this alters the properties of soil, making it unfit for agriculture and urbanization

Source(s): Authors' own work

mechanism and reasons for employing SD to analyze value chains (Muflikh *et al.*, 2021). Similarly, SD models helped to investigate the policy challenges prevailing in urban agriculture along the food value chains (Rich *et al.*, 2018). SD has been used in agricultural networks to improve profits by mitigating postharvest losses (Karthick *et al.*, 2023), enhancing water management, analyzing performance under dry conditions, and improving cropland expansion to improve net income and productivity.

2.3 Research gap

Many studies within the literature focus on the sustainability and efficiency of rice and wheat supply chains. They aimed to improve profit by incorporating the effects of internal and external parameters, natural resource constraints, information technology technologies, and transportation (Chung, 2018; Sharifi *et al*., 2024). However, no one has investigated large-scale sustainability in the SC by considering the multiple conflicting SDGs and the TBL components that affect government policy. For example, the literature does not focus on the agricultural land used for other purposes, the farmland area, or the different dimensions of TBL.

The initial phase of the study involves identifying the parameters along the dimensions of the TBL and ranking by AHP. The second phase develops a hierarchical model using ISM followed by clustering based on their relative importance using cross-impact matrix multiplication applied to classification (MICMAC). The final phase dealt with building a SD model to evaluate sustainability in terms of farmland area and land use for other purposes and subsequently building a SD model to evaluate sustainability in terms of farmland area and land use for other purposes (Rich *et al*., 2018). The outcomes were evaluated across four different SC network scenarios.

3. Methodology

3.1 Comparison of the parameters using the analytical hierarchy process

The study's objective was to rank parameters identified via a literature review based on their importance in achieving sustainability in RSC in the context of the primarily related SDGs, namely SDG 15, SDG 2.4.1., and SDG 6.4. Priorities assigned using this method depend on the experts' experience and knowledge. AHP, one of the most commonly used approaches for assigning parameter weights, was employed to identify relative importance through pair-wise comparison. The strength of this technique is its capability to produce reliable results with a small sample size. In the present study, twelve experts from academia (3 Professors), the agri-tech industry (1 Business owner; 1 Manager), policymakers in environment and climate change areas (2), and practitioners (4 farm owners; 1 manager) were chosen to rank the parameters hierarchically based on their relative levels of contribution towards the objective of the study. A pair-wise comparison matrix was developed with parameters arranged across rows and columns in the same order. Importance values ($x \in R, 0 < |x| \leq 5$) were assigned to each parameter by comparing them with every other parameter in pairs. The other half of the matrix is filled such that $A_{ij} = 1/A_{ji}$, where "*i*" and "*j*" indicate rows and columns respectively and $A_{ij} = 1$ where "*i*" = "*j*". The final priorities are obtained for each element in the relation.

The normalized pair-wise matrix was constructed by dividing values in each cell of Table 3 with the sum of all the values in that particular column. Then, the parameter weights were calculated as the average of all the values in each row (Table 4).

Table 3. Pair-wise comparison matrix

	1	2	3	4	5	6	7	8	9	10	11
Commercial land (1)	1	0.25	0.68	1.44	2.34	0.42	1.83	0.59	0.44	1.42	0.47
Farming Turnover (2)	4.04	1	1.42	3.84	3.27	2.45	3.82	1.21	1.83	2.39	1.58
Farmland Area (3)	1.48	0.70	1	3.41	2.53	2.16	3.22	0.87	1.27	1.85	1.51
Land demand (4)	0.69	0.26	0.29	1	2.20	1.04	2.10	0.68	0.54	0.55	0.87
Land price (5)	0.43	0.31	0.40	0.46	1	0.86	2.23	0.77	1.15	0.91	0.60
Per Capita water (6)	2.36	0.41	0.46	0.96	1.17	1	3.59	0.95	1.49	1.74	1.45
Population (7)	0.55	0.26	0.31	0.48	0.45	0.28	1	1.03	0.50	1.12	0.50
Production rate (8)	1.71	0.82	1.16	1.47	1.31	1.05	0.97	1	2.76	2.58	1.96
Rainfall (9)	2.29	0.55	0.79	1.85	0.87	0.67	2.01	0.36	1	2.55	1.58
Water consumption (10)	0.70	0.42	0.54	1.83	1.10	0.57	0.89	0.39	0.39	1	2.59
Water level (11)	2.14	0.63	0.66	1.15	1.68	0.69	2.00	0.51	0.63	0.39	1

Source: Authors' own work

Table 4. Normalized Pair-wise comparison matrix

	1	2	3	4	5	6	7	8	9	10	11	Criteria weight	Relative weights of criteria (percentage)
1	0.06	0.04	0.09	0.08	0.13	0.04	0.08	0.07	0.04	0.09	0.03	0.07	6.74
2	0.23	0.18	0.18	0.21	0.18	0.22	0.16	0.15	0.15	0.15	0.11	0.18	17.53
3	0.09	0.13	0.13	0.19	0.14	0.19	0.14	0.10	0.11	0.11	0.11	0.13	12.99
4	0.04	0.05	0.04	0.06	0.12	0.09	0.09	0.08	0.05	0.03	0.06	0.06	6.41
5	0.02	0.05	0.05	0.03	0.06	0.08	0.09	0.09	0.10	0.06	0.04	0.06	6.07
6	0.14	0.07	0.06	0.05	0.07	0.09	0.15	0.11	0.12	0.11	0.10	0.10	9.78
7	0.03	0.05	0.04	0.03	0.03	0.02	0.04	0.12	0.04	0.07	0.04	0.05	4.60
8	0.10	0.15	0.15	0.08	0.07	0.09	0.04	0.12	0.23	0.16	0.14	0.12	12.09
9	0.13	0.10	0.10	0.10	0.05	0.06	0.08	0.04	0.08	0.15	0.11	0.09	9.29
10	0.04	0.07	0.07	0.10	0.06	0.05	0.04	0.05	0.03	0.06	0.18	0.06	6.92
11	0.12	0.11	0.09	0.06	0.09	0.06	0.08	0.06	0.05	0.02	0.07	0.08	7.59

Source(s): Authors’ own work

The results of AHP were encouraging from an implementation standpoint. Farming turnover had the highest priority of 17.53%, followed by farmland area (12.99%) and production rate (12.09%). The consistency of the obtained results was verified by computing λ, which is the average of the product of the values in each cell with their respective criteria weights. Then the Consistency Index (CI) was determined as:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{1}$$

Random index is the CI obtained when the entities of matrix A are completely random. A consistent system must have a ratio. $\frac{CI}{RI} < 0.1$. In the present analysis, the ratio obtained was 0.059, confirming the system's consistency.

3.2 Development of a hierarchical model using Interpretive Structural Modeling

ISM is a proven technique to represent a complex problem structurally. It was employed to hierarchically sort the top eight parameters that influenced the sustainable RSC using the interrelationships between them (Narenthiran *et al.*, 2020). To develop the ISM model, the interrelationships between them were collected from the literature and experts (Table 5).

3.2.1 Structural self-interaction matrix. This matrix shows the direction of associations rather than their magnitude. A "leads to" type of association was defined between the parameters:

(1) V: parameter "*i*" affects "*j*"

(2) A: parameter "*j*" affects "*i*"

(3) X: parameters "*i*" and "*j*" affect each other

(4) O: parameters "*i*" and "*j*" do not affect each other

3.2.2 Reachability matrices. The structutal self interaction matrix (SSIM) which is developed based on pairwise comparison of variables. is transformed into the Initial Reachability Matrix (IRM) by replacing the alphabets with "1" and "0" to indicate the presence and absence of associations, respectively. The guidelines used for this transformation are:

V(i,j)→"1" in (i,j) and "0" in (j,i)

A(i,j) → "0" in (i,j) and "1" in (j,i)

X(i,j) → "1" in both (i,j) and (j,i)

O(i,j) → "0" in both (i,j) and (j,i)

The IRM is further converted to the Final Reachability Matrix (FRM) by denoting the transitivities by 1* (Table 6).

Table 5. Structural self-interaction matrix

S. No.	Parameter	1	2	3	4	5	6	7	8
1	Farming Turnover		O	A	O	O	O	O	V
2	Farmland Area			X	O	O	O	V	O
3	Production rate				O	O	V	O	O
4	Per Capita water					O	V	X	O
5	Rainfall						O	V	O
6	Water level							A	V
7	Water consumption rate								A
8	Commercial land area								

Source(s): Authors' own work

Table 6. Final reachability matrix

Parameter	1	2	3	4	5	6	7	8
1	1	0	0	0	0	0	1*	1
2	1*	1	1	1*	0	1*	1	0
3	1	1	1	0	0	1	1*	1*
4	0	0	0	1	0	1	1	1*
5	0	0	0	1*	1	1*	1	0
6	0	0	0	0	0	1	1*	1
7	0	0	0	1	0	1	1	1*
8	0	0	0	1*	0	1*	1	1

Source(s): Authors' own work

3.2.3 Level partition. The parameters were sorted into multiple levels based on their reachability, antecedent, and intersection sets (Table 7). Reachability and antecedent sets are influenced by and influence parameters, respectively, while the intersection set contains the common elements. Top-level parameters are those with the same reachability and intersection sets. These are eliminated from further iterations. This process is repeated until levels are assigned to all the parameters. Arranging the FRM based on the levels produces a conical matrix with the first-level parameters placed on the topmost row. The ISM model was formed after removing the transitive links to represent the parameters across multiple levels (Figure 1).

3.2.4 MICMAC analysis. MICMAC helps to cluster the parameters based on their driving and dependence powers. The parameters were grouped as autonomous (Quadrant-3), dependent (Quadrant-4), linkage (Quadrant-1), and driving (Quadrant-2) parameters (Figure 2).

Table 7. Level partition

Parameter	Reachability set	Antecedent set	Intersection	Level
1	1,7,8	1,2,3	1	II
2	1,2,3,4,6,7	2,3	2,3	III
3	1,2,3,6,7,8	2,3	2,3	III
4	4,6,7,8	2,4,5,7,8	4,7,8	II
5	4,5,6,7	5	5	III
6	6,7,8	2,3,4,5,6,7,8	6,7,8	I
7	4,6,7,8	1,2,3,4,5,6,7,8	4,6,7,8	I
8	4,6,7,8	1,3,4,6,7,8	4,6,7,8	I

Source(s): Authors' own work

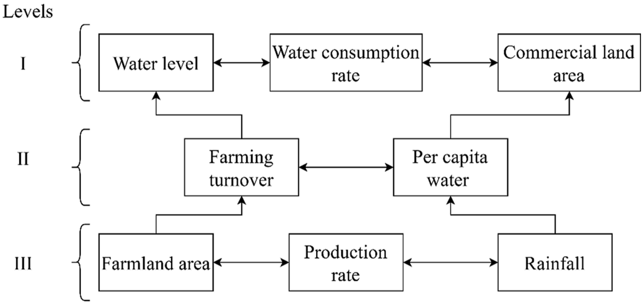


Figure 1. Digraph of the ISM model. Source: Authors' own work

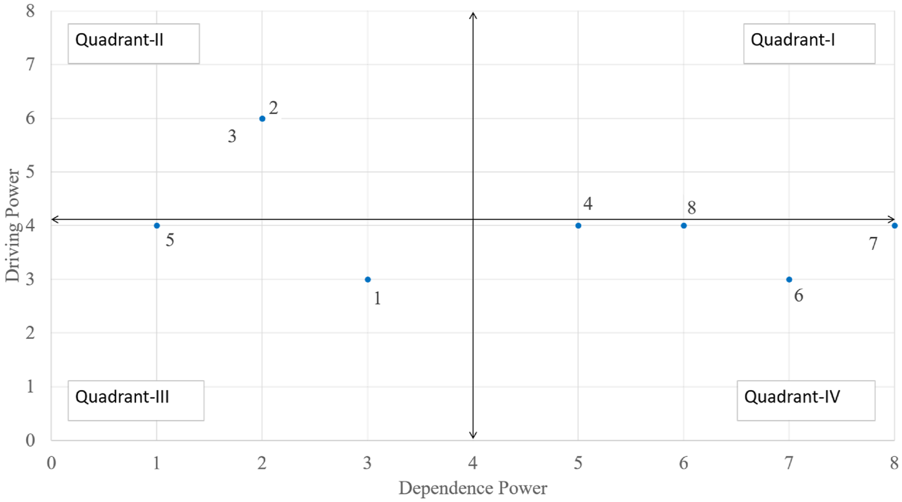


Figure 2. MICMAC analysis. Source: Authors' own work

The MICMAC plot (Figure 2) shows that the parameters, namely farmland area and production rate, are the driving parameters and are most important in the system. It is also clear that there are no linkage parameters. The production rate is a significant parameter in countries like India, which have lower yields and higher water consumption. The farmland area depends on other parameters, such as the commercial land area and water consumption rate. However, the parameters per capita water, water consumption rate, and commercial land area have a marginally low driving power and are, therefore, not classified as strong linkage parameters. Relatively higher driving powers of these parameters make them essential in the system. Their higher dependence makes them highly prone to changes whenever changes are made to the system. Population explosion and urbanization are the major causes of these three parameters, which remain significant reasons for the demotion of agriculture in India. There is a vital necessity to trade off the growth and utilization of resources considering the future generations. These three parameters, along with water level, are the dependent ones. Farming turnover and rainfall remain a part of the system and are of minimal importance. Turnover, however, depends on the practices followed by the farmers, whereas rainfall is a parameter that is out of the control of the practitioners. These could provide insights for policymakers and practitioners to carefully make changes to the parameters, anticipating changes that could be brought about.

3.3 Development of the system dynamics model

A stock and flow model was developed based on the relationships between factors using the SD approach in Vensim software and simulated over three years. This model consists of mathematical equations derived from the understanding of primary observations, literature, and opinions of the twelve experts chosen. The experts' inputs were uncovered and inputted throughout the models development to aid modifications based on suggestions regarding the associations between the parameters. Model validation was followed by a simulation of four scenarios to present effective ways to make the RSC more sustainable and fulfill the objectives. Finally, the simulation results were analyzed to understand how each scenario has affected the overall SC in various aspects. Challenges that must be overcome to develop the SD model are data unavailability, technological incapabilities, inadequate expertise (Kotir *et al.*, 2024), complexity and lack of stakeholder participation (Beall and Ford, 2010).

3.3.1 Data collection. The current study utilized the RSC in Tamil Nadu, and the information required for the simulation was gathered from official government websites (CARD, 2020; Department of Economics and Statistics, 2020). Forecasted data were used along with historical data where available.

3.3.2 Development of stock and flow model. The derived mathematical equations comprised three types of parameters, namely level, auxiliary, and constant, to draw the Causal Loop Diagram (CLD). The stock and flow diagram (Figure 3) was designed based on the mathematical equations and was included in the model to interlink the parameters. It extends the CLD to accumulate the values over time (Muflikh *et al.*, 2021). The simulation was performed to understand the dynamics of the model parameters and the flow of information and stocks in the SC. A base run simulation was performed to validate the model. Various leverage points were identified through this run, and different scenarios were designed for further analysis. Dynamic hypotheses are that subsidies, modern irrigation, and government laws affect the farmland area and land use for other purposes. Participatory modeling involving experts in the field was employed (Kotir *et al.*, 2024).

Parameters inputted into the simulation were obtained from relevant government websites.

3.3.3 Intervention scenarios. Scenarios that depict different interventions on the existing system are presented in Figure 4. Scenario 1 (Figure 4a) involves the compelled selling of the produce by farmers to the monopolies or customers directly at their bargain without the government imposing any regulations or defining the stipulated purchase price and targets SDG 1.4 and SDG 10.2. It is disadvantageous to the farmers as they are forced to give their

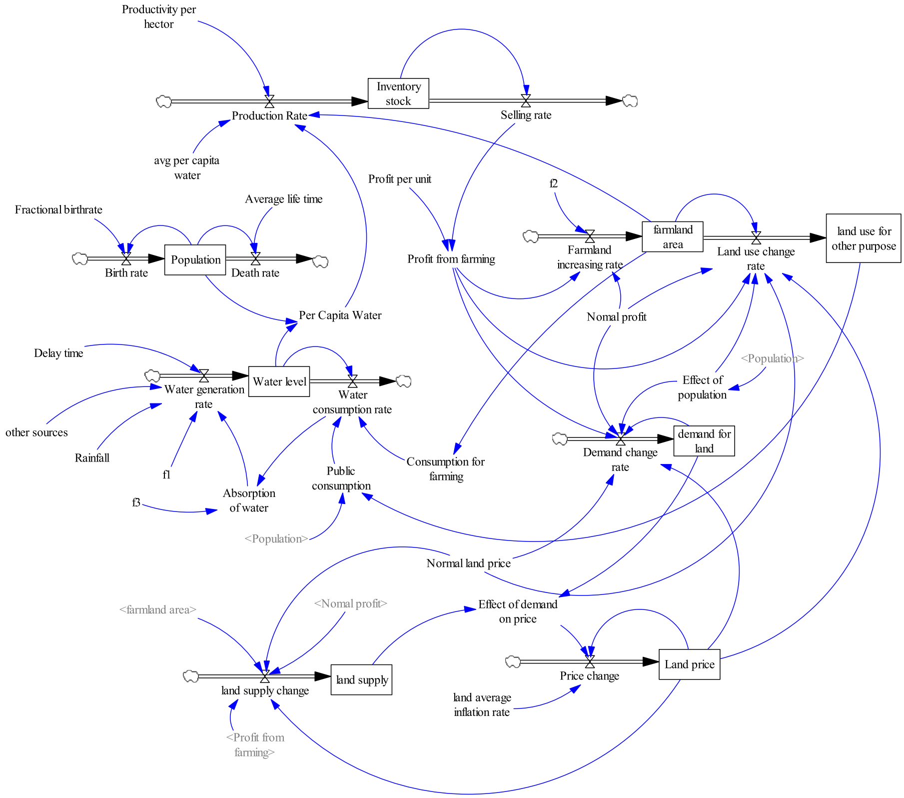


Figure 3. Stock and flow model. Source: Authors' own work

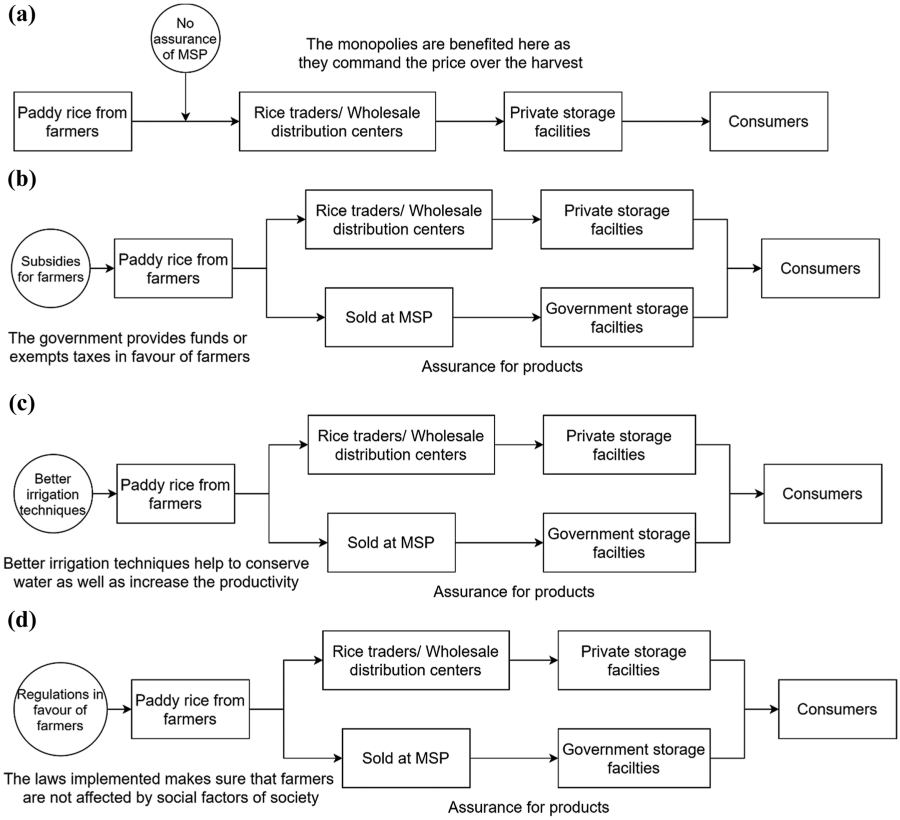


Figure 4. Intervention scenarios. Source: Authors' own work

products without having control over the selling price. It was taken as the base scenario that serves as the benchmark for improvement when interventions are introduced.

Scenario 2 (Figure 4b) explains the effects of allocating funds and providing tax exemptions in favor of farmers. This scenario presents the benefits provided to the farmers through finance or regulations. It could help them minimize their expenses in the production process. It was done assuming government regulations would affect the RSC's production and sustenance trend. Storage facilities also help farmers increase the shelf-life of produce while offering safe storage and reducing the need to sell the produce fast because of lack of storage and fear of wastage.

Scenario 3 (Figure 4c) substitutes conventional cultivation with modern irrigation techniques, where fruitful production can be obtained through reduced water consumption.

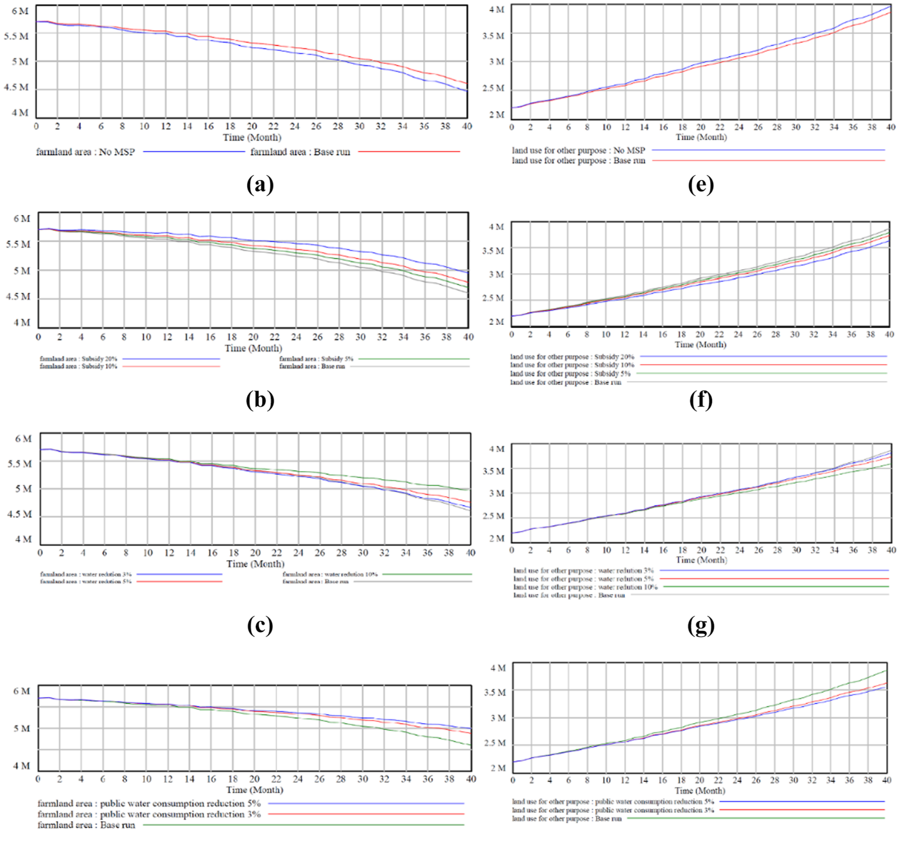
Industry 4.0 tools have proven effective in improving SC's performance and addressing many problems (Abdul-Rahaman and Abdulai, 2020). It aims at SDG 8.2 to improve productivity through innovation. Also, the expenses can be drastically lowered by generating maximum profit at potentially lesser water consumption, allowing even small-scale farmers to irrigate their fields more effectively. Government storage facilities have been considered simultaneously as they would augment the farmers' ability to use these tools along with the advantages such as increased shelf-life of produce, safe storage, and reduced fear of wastage.

In the 4th Scenario (Figure 4d), farmers are given explicit rights to the farming land, whereas the private stakeholders should bear extra taxes to acquire it. Also, outsourcing or overexploiting the available water to farmers will be dealt with following severe laws and regulations. It would allow the farming land to be sustained longer, targeting SDG 15 to prevent land degradation. It can be achieved through the efficient use of water (SDG 6.4) to suffice the needs of the growing population (SDG 2.4.1). It also includes Government storage facilities.

4. Results of simulation

The simulation results show the desired results except for the first scenario. Various sets of results in terms of changes in farmland area and land usage for other purposes have been discussed successively:

Results for Scenario 1: Since farmers are not guaranteed the MSP's as they are vulnerable to fickle market demands and the overpowering influence of market monopolies. A decline in the farmland area over three years when the farmers are not supported with MSP is presented in Figure 5a. It leads to land degradation and violates the SDG 15. The corresponding rate of change in land usage, i.e. land transformation, also increases for other purposes. Simulation



(a) (e)

(b) (f)

(c) (g)

(d) (h)

Figure 5. Results of Simulation a) to d): Farmland area for Scenarios 1 to 4; e) to h) Land usage for other purposes for Scenarios 1 to 4. Source: Authors' own work

results indicate that farmland and land used for other purposes have decreased by 4.17 and increased by 2.77% over the past three years. It is probably because of the selling of farmland by farmers due to low profits, which has made them struggle for livelihood. Contrarily, retaining farmland would have deprived them of profit and economic status. This forced behavior of selling land could be prevented if measures are taken to increase the MSPs considering the farmers' profitability.

Results for Scenario 2: In this scenario, the farmers are offered subsidies and financial support to reduce their expenditures and increase their profits. The variation in the change in farmland area and land use for other purposes with the change in subsidies given is shown in Figure 5 (b) and (f). The results are as expected based on the assumption that farmers generate lesser profit without subsidies. The plots of 5, 10, and 20% subsidies show improvement in results with an increase in the subsidy offered. Simulation results indicate that the farmland area increases by 1.88, 3.63, and 6.82% for subsidies of 5, 10, and 20% respectively. It indicates the direct relationship between subsidies and farmland retention, helping to attain SDG 15 and SDG 2 (by allowing enough produce to eradicate hunger). Subsequently, an increase in subsidies decreases the proportion of land use for other purposes by 1.65, 3.14 and 5.72% for subsidies of 5, 10 and 20%, respectively. These results facilitate deploying modern irrigation techniques to efficiently use the available/retained farmland to better achieve SDG 6.4 alongside SDG 2.4.1.

Results for Scenario 3: This scenario presents an implementation of modern irrigation techniques to reduce water wastage during irrigation and increase farmers overall productivity. However, this demands an initial investment in modern irrigation techniques. This can only be achieved if the farmers have sufficient profit from their produce. These would be challenging in the presence of hindrances, such as in scenario one. The extent of implementation of these techniques is indicated in the simulation by a reduction in the percentage of water, which is a direct output of modernization. Reduction in water by 3, 5, and 10% increases the farmland by 0.54, 2.06, and 5.42%, respectively. Also, this correspondingly decreases the land used for other purposes by 0.71, 2.19, and 5.30%, respectively. It reduces water consumption for irrigation whilst increasing productivity and reducing farmland conversion, improving agriculture's sustainability as defined in SDG 6.4. It is an essential marker to achieving zero hunger (SDG 2), reducing socioeconomic disparity (SDG 10.2), and sustainable management and efficient use of natural resources (SDG 12.2).

Results for Scenario 4: This scenario explains the results of imposing strict laws against activities that negatively impact farming. The main focus is preventing unauthorized digging of bore wells and the conversion of agricultural land for other purposes by increasing taxes and promoting SDG 2.4.1. that focuses on productive and sustainable agriculture. From a farmer's or practitioner's perspective, this would be meaningful only if they generate a decent enough profit for their livelihood. These activities are also measured by reducing the consumption of unauthorized water/overexploitation, pointing to SDG 12.2. Reducing water consumption by 3 and 5% increases the farmland area by 3.51 and 6.25%, respectively, and decreases the land used for other purposes by 4.68 and 6.33%, respectively. Each scenario affects multiple SDGs in different directions and proportions, which indicates that these have to be implemented in tandem with proper trade-offs. The feasibility of implementation in terms of cost, time, and resource constraints is to be considered.

5. Discussion

The eleven parameters that influence the sustenance of RSC were chosen with the help of twelve field experts. A pair-wise comparison was made using AHP to weigh these parameters. The strength of this technique lies in its ability to perform with fewer respondents. Results indicated that farming turnover (17.53%) and Farmland Area (12.99%) had the highest weights. The top eight parameters were considered for ISM and

MICMAC based on their relative weights. As a result, the production rate also emerged as an important parameter. These results and the interconnectedness of parameters emphasize the need to balance efficient water use (to improve productivity and retain farmland) while minimizing land conversion for other purposes as per SDG 15, i.e. zero net land degradation. ISM has been adopted by researchers in the past across diverse applications such as knowledge management in engineering industries to accomplish goals and measure the resilience of industries, for example, analyzing the effect of SC drivers in earthmoving and mining equipment manufacturing (Chand *et al.*, 2020), and improve sustainability through flexibility by evaluate the dimensions of SC survivability etc. A Stock and Flow model was developed to analyze the behavioral dynamics and large-scale effect of these parameters on the sustainability of the RSC network. The simulation aimed at generating more profit and improving the sustainability of agriculture. All the scenarios except for the first one produce profitable results for the farmers. As in scenario 2, providing subsidies encourages farming practices proportionately, evidenced by increased farmland and decreased land use for other purposes with an increase in subsidy offered. It showcases the improved sustainability of the sector due to the ability to retain crops for longer and improved bargaining power. Scenarios 3 and 4 enact the modernization of irrigation and imposition of strict laws against practices that demote farming, respectively. Applying Industry 4.0 tools has proved to be one of the most effective ways to promote the TBL sustainability. The extent of implementation of these practices has been indicated by a reduction in water usage, which is a direct indicator. These scenarios aim to address the water shortage, a major problem for farmers. Implementing these scenarios as required could address issues such as overexploitation of water, improve productivity, and generate more profits for the farmers.

The results project that farmland area used could be increased by offering subsidies to the farmers, implementing modern irrigation techniques to minimize wastage, and enforcing laws against illegal activities such as digging unauthorized borewells and converting agricultural land. SD models in the past have been applied to increase the profit of farmers and productivity by 7.6 and 1.4%, respectively (Suryani *et al.*, 2020), to bridge the gap between surplus and deficit by inter-territorial transfer (Alfa and Subagyo, 2018), and to attain self-sufficiency through increasing rice prices and eliminating monopoly (Chung, 2018). The Mixed-Integer Linear Mathematical model has been used to maximize profit across the SC (Jifroudi *et al.*, 2020) and assessment of the impact of price on the farmers and consumers and cluster first route second approach to reducing transport cost by grouping cultivators based on productivity levels. Ghadirian *et al.* (2023) analyzed the decline in agricultural land area and simulated five scenarios till 2041 by changing workforce, land, and water usage parameters. In addition to these findings in the literature, the present study has revealed some of the most vital parameters that influence the sustenance of the RSC.

Further, the prevailing problem of reducing farmland and converting agricultural land into residential or commercial lands has been simulated. Scenarios have been enacted to provide insights into policymaking. Some of the major results include increasing farmland area by 1.88, 3.63, and 6.82% by offering subsidies of 3, 5, and 10%, respectively, to farmers; increasing farmland by 0.54, 2.06, and 5.42% through the use of modern irrigation techniques to reduce water consumption by 5, 10, and 20% respectively; and increasing farmland area by 3.51 and 6.25% through the imposition of strict laws that reduces water consumption by 3, 5, and 10% respectively. These ultimately address the larger multiple SDGs problems, including poverty reduction, food security, and socioeconomic development.

Various scenarios created based on the different possible plans of action to address issues regarding farmland use and land use for other purposes are useful in understanding the effects of imposing different strategies to improve the sector’s sustainability. The work contributes highly to the theory by presenting a multi-phased approach to identifying the vital parameters for similar studies.

6. Implications

6.1 Theoretical implications

Research and development must balance satisfying the growing population's requirements, maintaining a rich biodiversity and improving productivity without compromising the environment (Hinz *et al.*, 2020). While promoting agri-tech, state-of-the-art technologies, and land use for agriculture remains important, the conflicts these could lead to are to be anticipated. For instance, the proposed alterations should be consistent with climate change mitigation plans (SDG 13) and land use for various purposes (SDG 15) (United Nations, 2023). The scenarios simulated in the present study reveal how various interventions are interrelated and need to be traded off, considering their impact on the target parameter. The multi-phased approach also adds to the validity of the influence of the chosen parameters on the outcomes—studies like this synergize Systems thinking, the TBL, and SDGs. It enables organizations to internalize SDGs based on identified variables. This approach also demonstrates the purpose of deploying larger or global frameworks with localized policies for a business setting. The simulation approach further enhances evidence-based decision-making in the context. While systems thinking offers a holistic approach, the other two theories carefully explain how trade-offs between various dimensions of policymaking are essential. The quantified results of farmland use and land use for other purposes could be mapped to the anticipated food requirement to make decisions based on various SDGs: addressing the need of the growing population (SDG 2.4.1) through efficient use of water (SDG 6.4) to maintain zero net land degradation (SDG 15). The work also unleashes the potential of the SD modeling approach to model larger systems connecting flows between internal and external parameters. It can be used where evidence-based strategic decisions play a vital role. Expanding this idea, other simulation approaches like Agent-based Modeling and discrete-event simulation (DES) could be employed to study granular data with agent-interaction and process-related data for operational-level decisions and to analyze the role or impact of each player in the network.

Several other interventions could also be simulated to see their individual and combined effects. The dynamics of biological processes that affect productivity could be included depending on the crops being studied (Muflikh *et al.*, 2021). These models need to be analyzed at different levels, as Maani and Cavana (2007) presented. These levels of thinking were applied to complete the problem design:

(1) Events – reduction in farmland and conversion of land use for other purposes

(2) Patterns – observing the patterns of why these occur (implications based on the parameters)

(3) Systemic structures – understanding of the characteristics of parameters and system holistically to develop scenarios and interventional mental models – beliefs and thoughts of the experts about the RSC

The effect of socioeconomic parameters, such as population density, economic development, urbanization, etc., could be studied across different demographics and for various crops to understand the holistic transition required across the country. These provide evidence for policymaking.

6.2 Managerial implications

The government plays a significant role in supporting the sustainability of the agricultural sector. Some factors, such as political lobbying, have been responsible for converting Rice fields for commercial purposes in India. The migration of the younger generation of farmers in search of livelihood and better employment opportunities has led to them selling the fields due to the inability to practice farming or needing money. Foreign remittances have forced families to lease out or sell their land(s) in want of money. Also, the inflow of cash from abroad has led to the conversion of Rice fields into commercial buildings and resorts (Azeez and Nikhil Raj, 2015). These could be minimized if the farmers earn more profit in their profession. However, these decisions require an understanding of parameters that affect multiple dimensions. Approaches similar to that in the present study that include multiple dimensions of TBL are handy. Additionally, addressing SDGs helps the organizations align with the goals of the United Nations, motivating organizations and businesses to work towards a larger objective. Simulation-based approaches enable businesses to compare alternatives and implement the most feasible ones. Sustainability enhancement through simulation employment helps reduce the cost and time involved and the risks of making changes in the actual network (Karthick *et al.*, 2023).

Creating awareness about using the latest technologies would benefit small-scale and rural farmers by introducing schemes or bodies encouraging farmers to borrow money through local credit or savings. The hesitancy of banks to lend to small-scale farmers and the absence of such schemes trigger them to seek other employment opportunities. It leads to the sale and conversion of farmland for other purposes. To tackle this, the government could introduce diversification in non-agricultural tasks to make the farmers self-sufficient to fund their purchases. Involving Non-Governmental Organizations could be effective in reaching a wider population. The ideologies discussed, and the scenarios analyzed in this study could be tailored to the scenario.

Targeted interventions such as identifying and hiring skilled laborers and providing food and shelter in addition to their wages might attract them to work. It is an unsustainable practice as the regulations imposed must drive transformation alongside ensuring non-negative returns. Practices such as intertwined supply networks, wherein the organizational networks work together, could be effective. It would allow overall growth as each organization could support others in the aspects that they pioneer in. Schemes such as the Targeted Public Distribution System that offers help to rural and poor households below the poverty line can be emphasized in relation to SDG 1 to eradicate poverty. Work must be done on unforeseen negative impacts that reduce the interest of farmers in rice production. The government can initiate direct procurement from farmers to increase their profit. Fragmentation of land needs to be prevented by increasing the rural-urban continuum. Governments must focus on distributing the developments to minimize the disparity across locations. It could also reduce the fragmentation of joint families, which ultimately reduces the family labor, increases dependence on hired labor, accelerates the need to generate more income using smaller land, shifts towards cash crops, etc. It might prevent the achievement of SDG 2 (zero hunger) thus having long-term detrimental effects. Governments must understand such implications using Systems thinking, first principles thinking, etc., to devise policies and transform the network structure to foster sustainable practices. Internalizing SDGs through variables affecting business outcomes helps map organizational TBL goals to global targets.

7. Conclusion

The study provides a comprehensive framework to address sustainability in the RSC. Considering the SDG targets enabled the simultaneous assessment of the specific roles of variables across one or more dimensions of the TBL. It paves the way for corporate frameworks to be devised based on global SDGs, enabling businesses to translate the TBL-based performance indicators into SDG targets. Though research in the past has worked on improving the profit and performance of various agricultural SCs, a deeper investigation into the cause leading to a long-term disruption is missing. The importance of addressing such critical issues, the farmland area, and land transformation for commercial purposes motivated us to do this research. To offer insights for real-time policymaking, we chose parameters across the dimensions of TBL and focused on generating scenarios and strategies targeted towards SDGs. Leveraging proven techniques like AHP, ISM, and SD, this research identifies key parameters, including farmland area, production rate, and water consumption, as critical drivers of sustainability. The scenarios enacted through simulation such as providing subsidies, modernizing irrigation practices, and enforcing regulations—significantly enhance sustainability outcomes. For instance, increasing subsidies directly correlates with higher farmland retention, aligning with SDG 15 (Life on Land) and SDG 2 (Zero hunger). At the same time, modern irrigation practices improve water-use efficiency, addressing SDG 6 (Clean Water and Sanitation). These insights underscore the necessity of a balanced approach as individual interventions impact multiple SDGs with varying magnitudes. These reflect some of the important SDGs, such as SDG 2.4.1. that measures the proportion of agricultural area under productive and sustainable agriculture to promote zero hunger, SDG 6.4., which focuses on efficient water use, and SDG 15, which aims at zero net land degradation.

The effects of the scenarios have managerial and theoretical implications on multiple SDGs and various dimensions of the TBL. Government policies must consider trading off these interventions to achieve the target as each has different magnitudes and alignment of impact on the target parameters, i.e. farmland area and land use for other purposes. The tailored implementation of these scenarios could achieve them. Some important conclusions were also drawn from the study. The need for more profits from RSC activities has driven farmers to sell their farmland for other commercial uses. These have led to water shortages due to the digging of unauthorized wells and an increase in the land price, thereby decreasing farming activities. The simulation revealed the system’s behavior under several circumstances and exposed the leverage points, namely, farmland area and water availability. Four scenarios designed on these leverage points improved the system’s performance. These could expose the points of focus that an SC needs to work on to improve productivity.

The present study focuses on the rice crop in India. It could be extended to other crops and geographies. The ranking of parameters and development of the conceptual model might be subject to bias as the associations defined are purely based on the understanding and subject knowledge of the experts involved in the study. Future studies could be conducted across various geographies to assess the differences across different territories. The simulation could be applied to a large-scale network to understand the behavior of system changes. Also, additional interventions could be performed to portray possible scenarios and their outcomes in achieving the objectives. It could be helpful for regulators and policymakers to devise suitable strategies as each system in real-time would demand tailored interventions depending on the nature of operations and interaction among the entities of the system.

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