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RESEARCH PAPER

Sustainability and the soybean supply chain in Brazil: challenges and implications through the lens of the current reality tree

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ABSTRACT

Goal: This study examines the sustainability of Brazil's soybean supply chain, highlighting deficiencies despite limited initiatives. It utilizes the Theory of Constraints (TOC), specifically the Current Reality Tree (CRT), to identify and address sustainability challenges.

Design/Methodology/Approach: Eleven interviews with supply chain representatives were conducted to identify sustainability barriers. The CRT tool maps undesirable effects and root causes across environmental, social, and economic dimensions.

Results: Economic sustainability exhibited the highest number of underlying causes, followed by environmental and social pillars. Key issues include strained inter-chain relationships impacting economic outcomes, the imperative for eco-friendly practices and technologies, and the importance of community and employee development. Additionally, eight leverage points for improvement, such as Defensive agricultural practices exceeding permitted levels, were identified, and their implications discussed.

Practical implications: Insights suggest strategic interventions to enhance supply chain sustainability, emphasizing collaborative efforts, environmental stewardship, and human resource development. Addressing sustainability gaps could foster better socio-economic conditions within local communities and improve the overall industry reputation.

Limitations of the investigation: The study's scope is limited to the soybean supply chain in Brazil, potentially constraining generalizability. Future research could broaden the focus to include other agricultural sectors, global comparisons, or involve additional stakeholders to provide a more comprehensive perspective.

Originality/Value: This research uniquely applies TOC's CRT to analyze sustainability in a major agricultural supply chain, offering actionable insights and highlighting critical areas for improvement.

Keywords: Theory of constraints; Soybean supply chain; Sustainable Food Supply Chain.

1 INTRODUCTION

When planning for soybean production, it's essential to consider factors such as climate, rainfall, soil preparation and management, seed quality and storage, and weed control. Moreover, Gazzoni (2013) urged that sowing at the appropriate time, utilizing harvesting technology, proper grain

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storage, and establishing logistics for sale and export are additional elements that must be considered before cultivation can commence.

The soybean industry's supply chains are currently experiencing mounting pressure from customers and governments to prioritize sustainable development. As a result, profit-driven strategies are being redirected toward a more holistic approach that considers the triple bottom line (TBL), composed of economic (profit), environmental (planet), and social (people) pillars (Jia *et al.*, 2020).

Several studies address the concept of TBL sustainability in food supply chains. For example, Kruger *et al.* (2022) developed a sustainability assessment model for a swine supply chain based on a literature review and expert interviews. Similarly, Carvalho *et al.* (2022) created a roadmap for evaluating sustainability in the agri-food supply chain. The study involved interviews with producers, processors, third-party logistics providers, retailers, and waste recovery and valuation operators. In turn, Ada (2022) present factors that impact sustainability in agri-food chains, even though they do not make it clear what factors should be prioritized for improvements. Silva *et al.* (2025) explores the relationship between sustainability and the complexity of the food supply chain (FSC), highlighting the importance of adopting a sustainable approach that balances financial growth, environmental preservation, and social well-being. The study emphasizes the need for practical actions, such as employee training and waste management policies, to promote sustainability in the FSC and minimize negative impacts.

All the studies analyzed address the three pillars of sustainability: economic, environmental, and social, following the Triple Bottom Line (TBL) framework. However, they differ in their methodological approaches. Carvalho *et al.* (2022) and Kruger *et al.* adopt predominantly qualitative methods. Carvalho *et al.* (2022) use a multi-method approach, combining a structured literature review and semi-structured interviews with key stakeholders. Kruger *et al.* (2022) apply the Delphi method to gather expert opinions and validate their sustainability assessment model. In contrast, Silva *et al.* (2025) and Ada (2022) take a quantitative approach. Silva *et al.* (2025) employ a survey with 379 respondents and principal component analysis (PCA) to examine the relationship between sustainability and supply chain complexity, whereas Ada (2022) utilizes a hybrid decision-making model (FANP and fuzzy VIKOR) to evaluate and rank sustainable suppliers. All studies rely on real-world data and can be considered empirical; however, their empirical validation and generalizability levels vary.

Kruger *et al.* (2022) and Ada (2022) test their models within specific supply chains. Kruger *et al.* (2022) in three companies from the pork supply chain in Brazil and Ada in an agribusiness company in Turkey, providing practical validation but within limited contexts. Carvalho *et al.* (2022) gather insights from industry stakeholders but do not empirically test their proposed roadmap directly, which limits its practical applicability. With its large dataset, Silva *et al.* (2025) offer broader statistical generalizability, unlike the more context-specific findings of the other studies.

Although these studies have made significant contributions toward understanding sustainability in agri-food supply chains, there remains a need for further research to determine which factors should be prioritized for improvement (Jia *et al.*, 2020; Williams *et al.*, 2017) . The social, economic, and environmental aspects of sustainability in the soybean supply chain have been the subject of recent research that has yielded important new insights. The effects of employing microorganisms in Indonesian soybean cultivation are examined by Junaidi *et al.* (2024), emphasizing the advantages for sustainability, the economy, and the environment. Dreoni (2022), in a systematic review, realized that there is conflicting and limited research regarding the effects of soybean cultivation on multifaceted well-being. The effects of soybean production on ecosystem services hurt people and the environment. Virtually little data demonstrates how sustainable value chain policies affect people's well-being. Policies for sustainable soybeans must take a broader variety of social implications into account. Toloi *et al.* (2021), examine the economic, social, and environmental effects of soybean production in Mato Grosso, Brazil. The Driver-Pressure-State-Impact-Response framework explores the connections between environmental sustainability, development, and production. The findings by Sharifi *et al.* (2023) demonstrate the importance of strategy as an integrated approach that integrates sustainability pillars in soybean supply chains. Furthermore, the results show that the stochastic multi-objective model can control fluctuations in uncertain parameters.

Despite the existence of these studies, no research mentions explicitly using the Theory of Constraints (TOC) as the method of analysis in sustainable supply chain management. According to Stefano *et al.* (2024), the Theory of Constraints (TOC) offers a solution for supply chains focused on increasing sales throughput while reducing inventory levels.

Developing more comprehensive and integrated assessment frameworks that capture these chains' complex and dynamic nature is necessary to achieve more sustainable outcomes. The Theory of Constraints (TOC) Thinking Process offers a systems-based alternative to address cause-effect relationships to pinpoint the constraints that explain undesirable effects (Goldratt-Ashlag and Goldratt, 2013). TOC has a long history of application to many problems and sectors. For example, TOC was applied in India's largest lock manufacturing company, where the main restrictions that limited the company's performance in production, distribution, supply group, and projects were identified and eliminated over seven years (Modi *et al.*, 2019). In the electric transport industry, TOC was used to identify production and market bottlenecks for the spread of electric vehicles (Naor *et al.*, 2021). In line with a constraint mitigation methodology was proposed to optimize supply chain transportation costs between manufacturers and distributors in a beverage unit in Bangladesh (Naor *et al.*, 2021).

The rationale for employing TOC to analyze sustainability in soybean supply chains lies in its ability to tackle complex problems without needing advanced analytical or probabilistic solutions (Bauer *et al.*, 2019). Due to increasing pressure on the soybean supply chain to adopt sustainable practices, driven by growing concerns from customers and governments regarding environmental and social impacts, the soybean supply chain in Brazil, a major global producer, faces unique sustainability challenges (Gholian-Jouybari *et al.*, 2023; Jia *et al.*, 2020). These challenges require a comprehensive evaluation of their practices and effects. In order to enhance sustainability practices along the chain and advance better environmental, social, and economic outcomes, this research offers practical insights and suggestions. This study uses the Theory of Constraints (TOC) methodology, specifically through the Current Reality Tree (CRT). A qualitative approach to comprehensively analyze the soybean supply chain's sustainability. The research question addressed by this study is stated as follows: how do environmental, social, and economic factors contribute to the sustainability of the soybean supply chain? This paper aims to employ a Current Reality Tree (CRT) to structure the undesired effects and basic causes that affect the sustainability of the soybean supply chain, thereby providing insights into potential improvements and interventions that can enhance its overall sustainability.

2 THEORETICAL FRAMEWORK

2.1 Sustainable supply chains

The definition of sustainable development was first developed by the World Commission on Environment and Development at the United Nations General Assembly in 1987. The Commission's report, also known as the "Our Common Future Report" or Brundtland Report, defined sustainable development as "the human ability to ensure that the current development meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). According to Vafaei *et al.* (2019), the results indicate that organizations should prioritize the application of sustainable process management principles to promote better coordination between departments and organizational resources. In addition, the author recommends that organizations emphasize innovative and creative activities to achieve a sustainable competitive advantage through sustainable practices in the supply chain.

As mentioned, the TBL concept is central to the sustainability organizational goal of achieving economic, environmental, and social success (Elkington, 1998; Liu *et al.*, 2019). Despite the importance of economic sustainability, which aims to reduce costs, the TBL has not received adequate attention from researchers, particularly in developing economies (Nayal *et al.*, 2021; Tang, 2018).

Sarkis *et al.* (2010) argue that the social pillar encompasses individual and societal well-being by effectively managing social resources. In many developing nations, poverty, limited access to education, and negligent law enforcement are common, resulting in severe social problems such as child and forced labor, low wages, extended work hours, gender-based discrimination, poor working conditions, violations of labor rights, delayed payment, non-compliant overtime wage payment, intimidation, restricted freedom of association, and poor supervisory and managerial practices (Govindan *et al.*, 2021).

The economic pillar focuses on profitability and cost reduction through sustainable practices, including lowering production costs, transaction costs, transportation and distribution costs, capacity change costs, and environmental costs, such as energy-related expenses (Alfonso *et al.*, 2021; Nayal *et al.*, 2025).

The environmental pillar is typically evaluated using indicators such as water and land usage, biodiversity, energy efficiency, greenhouse gas and ammonia emissions, nutrient and pesticide contamination (Caetano *et al.*, 2023; Thomassen and de Boer, 2005).

Singh and Srivastava (2022), argue that the social pillar directly enhances the impact of economic and environmental enablers on sustainability. To achieve a sustainable agricultural supply chain, agricultural enterprises and supply chains must adopt innovative policies and practices based on social sustainability. According to Hourneaux Jr *et al.* (2022), a set of indicators that covers the essential aspects of sustainable performance can aid in managing industrial enterprises with the TBL strategy. When assessing sustainability, it is necessary to consider all dimensions simultaneously, as prioritizing one dimension may lead to neglecting conclusions regarding the others (Singh and Srivastava, 2022). However, TBL implementation for sustainability is still inadequate in emerging economies like Brazil (Singh and Srivastava, 2022), where balancing agricultural interests with natural resource conservation is a primary concern (Magalhães *et al.*, 2020). According to the case study on the Ghanaian cocoa supply chain developed by Quayson *et al.* (2024), it is important to identify and prioritize barriers to implementing blockchain technology to manage supply chains sustainably, highlighting the lack of management support, customer awareness, security challenges and the absence of ethical practices as the main obstacles. For the field, when evaluating the enablers of blockchain in the sustainable supply chain, it is important to have a framework and methodology useful for decision-makers and managers, helping them develop strategies to improve the transparency and sustainability of agricultural supply chains with the effective use of blockchain (Bai *et al.*, 2022). Furthermore, supply chains are becoming more resilient and sustainable due to digital technologies like cloud computing, blockchain, and the Internet of Things (IoT), especially in emergencies like the COVID-19 pandemic and climate change. A framework that connects these technologies to stakeholder salience and sustainable supply chain strategies is proposed by Helms *et al.* (2024).

2.2 The soybean supply chain in Brazil

The soybean production chain in Brazil plays a fundamental role in the country's economy, with Brazil being one of the largest global producers and exporters of this commodity (Filassi and de Oliveira, 2022). Soybean cultivation in the country is carried out mainly in the Central-West, South, and North regions, emphasizing states such as Mato Grosso, Paraná, and Rio Grande do Sul (Medina, 2022). Several industries use Brazilian soybeans, including food, biodiesel, and animal feed. They also serve as an important export product, with China being one of the leading destinations (Rico and Sauer, 2015).

However, the expansion of soybean production in Brazil has raised environmental concerns, especially regarding the overuse of natural resources (van Berkum and Bindraban, 2008). The greatest commercialization of soybeans may intensify pressure on tropical forests, ecosystems, water resources, and biodiversity. Using inappropriate agricultural practices, such as illegal deforestation and intensive monoculture, contributes to environmental degradation, increasing greenhouse gas emissions, and affecting soil and water quality (Fearnside, 2001).

According to Péra *et al.* (2019), it is important to study and evaluate strategies to promote green corridors for soybean exports from Brazil to China by analyzing the optimal logistics routes regarding transportation costs and CO_2 emissions, highlighting the adoption of multimodal transport to achieve more sustainable logistics, and highlighting the positive impacts of investments in port infrastructure. The analysis utilizes a linear programming model solved in GAMS. In recent years, technologies such as precision agriculture and integrated crop-livestock-forestry (ILPF) have been encouraged, allowing for greater productivity with less environmental impact (Behling *et al.*, 2023). Therefore, a combination of technological innovation, public policies, and responsible agricultural practices is required to balance global demand and environmental preservation in the soybean production chain in Brazil.

Recent studies highlight the importance of sustainability in the soybean production chain. Valuing soy by-products reduces environmental damage and combats malnutrition, claim Singh and Krishnaswamy (2022). To promote a sustainable food system, their review suggests a zero-waste model and identifies efficient and economical solutions for using the by-products of soybean processing. The authors highlight that transformational leadership and stakeholder engagement positively impact business sustainability in soy-based Micro Small Medium Enterprises, West Java, with the social dimension more substantial than the environmental one. Influencing employees and building trust is critical to business Sustainability (Kurniawati and Sulaeman, 2022). Based on field research conducted in Brazil, the essay examines how human rights, and the environment are integrated into soy supply chains from Brazil to Europe, highlighting regulations like the Soy Moratorium, the Working Group on the Cerrado, the Round Table on Responsible Soy, and the European Union Regulation on deforestation-free products (Schilling-Vacaflor and Gustafsson, 2024).

While these studies contribute significantly to understanding sustainability in soybean production, they present some contradictions and gaps. For instance, while some research emphasizes technological solutions such as precision agriculture (Behling *et al.*, 2023), others focus on regulatory frameworks and human rights concerns (Schilling-Vacaflor and Gustafsson, 2024). This divergence suggests a lack of consensus on the most effective approach to achieving sustainability in the sector. Additionally, studies such as those by Singh and Krishnaswamy (2022), focus on soy by-products and their potential for sustainability, yet do not address the broader environmental impacts of large-scale soybean monoculture.

Moreover, there is limited discussion on holistically integrating economic, social, and environmental dimensions. The emphasis on logistics and infrastructure (Péra *et al.*, 2019) improvements contrasts with calls for stronger regulatory oversight (Schilling-Vacaflor and Gustafsson, 2024), highlighting a gap in strategies that simultaneously enhance productivity and enforce environmental responsibility. Furthermore, despite the growing body of research on sustainability, none of these studies utilize the Theory of Constraints, which could help identify critical leverage points to optimize the soybean production system. Addressing these inconsistencies and filling these gaps through interdisciplinary approaches could enhance the overall effectiveness of sustainability efforts in the soybean production chain.

2.3 Theory of Constraints (TOC)

TOC is a systematic thinking strategy that posits that all complex systems in real life, including business organizations, are controlled by linkages between causes and effects (Cox III and Schleier, 2013). The TOC approach consists of five steps: identifying the system constraint, maximizing the exploitation of the constraint, subordinating everything else to the policy of exploiting restrictions, increasing the restriction, and, as soon as the constraint is broken, returning to the first step to prevent the inertia of current policies from becoming a new constraint (Goldratt, 1990).

The term "interactive complexity" refers to sets of events that occur in a random or unforeseen order, as opposed to linear interaction, which occurs in a predictable, recognizable, observable, and planned manner (Perrow, 1999). However, it is worth noting that complex systems can be linear, which means that events occur linearly instead of being simple or devoid of complexity. For instance, the food supply chain is linear since it comprises complex but understandable operations. While mishaps may occur in these systems, their linearity enables the effects of such events to be discovered and fixed more quickly (Perrow, 1999). In this context, the Theory of Constraints (TOC) offers tools that can be individually or locally integrated (Librelato *et al.*, 2014). It proposes that the problems encountered by various organizational functions are interrelated and symptomatic of a few factors or basic causes, known as constraints (Dettmer, 1998). Constraints can take on various forms, including physical constraints such as limited raw materials and machine capacity, but often, constraints (Maranhão *et al.*, 2019).

The TOC approach includes the Current Reality Tree (CRT) diagram, which provides a comprehensive view of the system's current state under consideration. The CRT enables the identification of system constraints, which can be used to guide discussions on the necessary interventions. One of the key benefits of the CRT is its ability to present complex scenarios succinctly by highlighting the basic causes of perceived problems within the system (Mason-Jones *et al.*, 2022; Turan and Ozturkoglu, 2022).

The Theory of Constraints (TOC) has been widely applied across various sectors to optimize processes, increase efficiency, and eliminate bottlenecks. Notably, companies adopted TOC to reduce production times and enhance the efficiency of their supply chains (Simatupang *et al.*, 2004). In this context, the Drum-Buffer-Rope (DBR) methodology has significantly contributed to minimizing delays and improving efficiency in patient care (Cox III and Mabin, 2025). Similarly, retail chains have applied TOC principles to improve inventory management and reduce supply disruptions, thereby increasing product availability without raising logistics costs (Modi *et al.*, 2019). In agriculture, TOC has been used to identify constraints in logistics and food processing, ensuring more predictable supply chains and reducing waste (Abdulai, 2016). Adopting the Current Reality Tree (CRT) has enabled agricultural supply chain managers to map the basic causes of grain production and distribution bottlenecks. These examples highlight the versatility of TOC and its applicability across various contexts, including the agro-industrial sector. Specifically, in the case of the soybean supply chain in Brazil, applying TOC and CRT provides a structured approach to analyzing sustainability challenges, supporting the development of practical and strategic solutions.

TOC posits that organizational improvement can only occur when its constraints are removed (Goldratt and Cox, 2016). Therefore, TOC provides managers with a set of tools and Thinking Process (TP) approaches to enhance performance (Goldratt and Weiss, 2005). The TP uses three primary questions to guide change management and identify the basic cause of undesirable effects (UDEs): "What to change," "What to change to," and "How to cause the change" (Dettmer, 1998; Scheinkopf, 1999). The "What to change" question aims to identify the core issues responsible for UDEs, and the CRT is the prive this objective (Cox III *et al.*, 2010).

TOC is put into practice by linking UDEs with propositions in the form of "if...then..." statements (Naor *et al.*, 2021). Since the first UDEs are the primary effect without any secondary effects, they are the ones that most people can readily observe or identify. The inter-media effects, located in the center of the CRT, often have multiple impacts, making it essential to make concerted efforts to eliminate them. The foundational elements of the tree represent the basic causes that give rise to all other UDEs. Despite their critical role, these elements are often overlooked, and their impacts are underestimated.

Figure 1 presents how to read the CRT. Figure 1 (a) presents a simple arrangement: if the cause occurs, it produces the result. Figure 1 (b) represents an additional cause: if either the cause or the additional cause occurs, then the effect manifests. Figure 1 (c) if the cause and necessary cause are present, then the effect occurs (Noreen *et al.*, 1996).

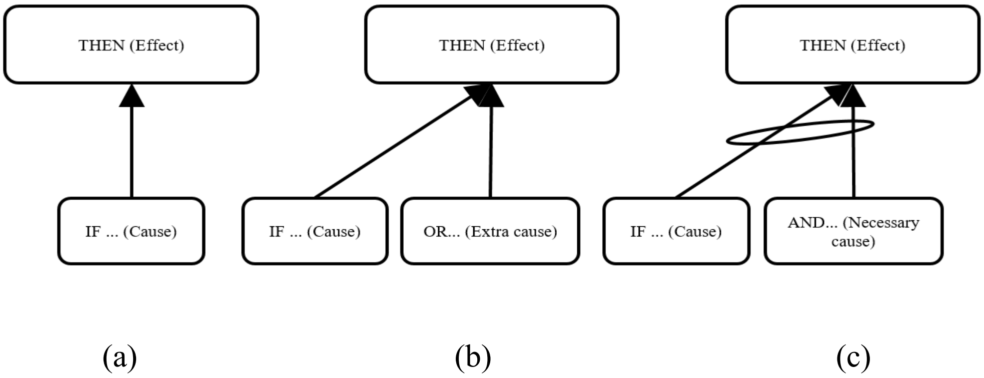

Figure 1 - Interpret the CRT. Source: The authors themselves

CRT is a valuable technique for determining the common causes of various outcomes. "Basic causes" do not have an arrow pointing to them; investigators must further examine them to ensure they are legitimate. Identifying these basic causes is directly linked to the Theory of Constraints' core principle of inherent simplicity, which maintains that a small number of elements govern any aspect of reality, and that one can resolve conflicts (Eidelwein *et al.*, 2018; Gomes *et al.*, 2022). In this sense, TOC posits that every complex system possesses an underlying simplicity whereby a few constraints or leverage points determine its overall performance (Cox III and Schleier, 2013).

When comparing the Theory of Constraints (TOC) with the Life Cycle Assessment (LCA) and Circular Economy (CE) models, each approach offers distinct contributions to optimizing and sustaining production systems. TOC focuses on identifying and addressing bottlenecks within a system to improve overall efficiency and maximize output. In contrast, LCA assesses the environmental impact of a product throughout its entire life cycle, from raw material extraction to disposal, allowing for a comprehensive evaluation of sustainability (Alejandrino *et al.*, 2021). On the other hand, Circular Economy models emphasize resource efficiency, waste reduction, and the continuous use of materials by promoting recycling, reuse, and sustainable design. (Gedam *et al.*, 2021; Walker *et al.*, 2022). While TOC is primarily concerned with optimizing constraints to enhance productivity, LCA and CE provide a broader perspective on sustainability by considering environmental and resource management factors. Integrating these approaches could offer a more balanced strategy, ensuring operational efficiency and long-term environmental responsibility in the soybean production chain.

3 RESEARCH METHOD

A case study was conducted to investigate the factors influencing the sustainability of the soybean supply chain and the measures for improvement. Given the complexity of the phenomenon under investigation, a case study approach was deemed appropriate (Yin, 2006) for identifying empirical relationships between variables (Starman, 2013).

3.1 Stages of the research method

Figure 2 illustrates the stages of the research method employed in this study, which followed a qualitative approach, based on the steps outlined and adapted by Serrano *et al.* (2019). The first stage consisted of a theoretical review to gather and analyze fundamental concepts related to the topic, emphasizing the application of the Theory of Constraints (TOC) and characterization of the chain, seeking to understand its structure, functioning, and main elements. Based on these, the theoretical framework was constructed, which served as a foundation for developing the case study. In the next stage, data collection began, guided by a previously prepared research protocol.

In this phase, the interviewee selection was also based on previously defined criteria. The selection of interviewees marked the beginning of the third stage, corresponding to the development of the case study.

The fourth stage comprised the data analysis through content analysis, allowing the extraction of information relevant to the research objectives. Followed by the 5th stage, which identified the variables that influence or characterize the main aspects of the problem investigated. Next, the Current Reality Tree (CRT) was constructed, a tool derived from the Theory of Constraints used to map undesirable effects and their root causes. The seventh stage involved analyzing the consistency of the CRT, ensuring the logic and coherence of the cause-and-effect relationships established, and making the necessary adjustments. Finally, the last stage corresponds to the conclusion of the study, in which the research's main results, limitations, and contributions are presented.

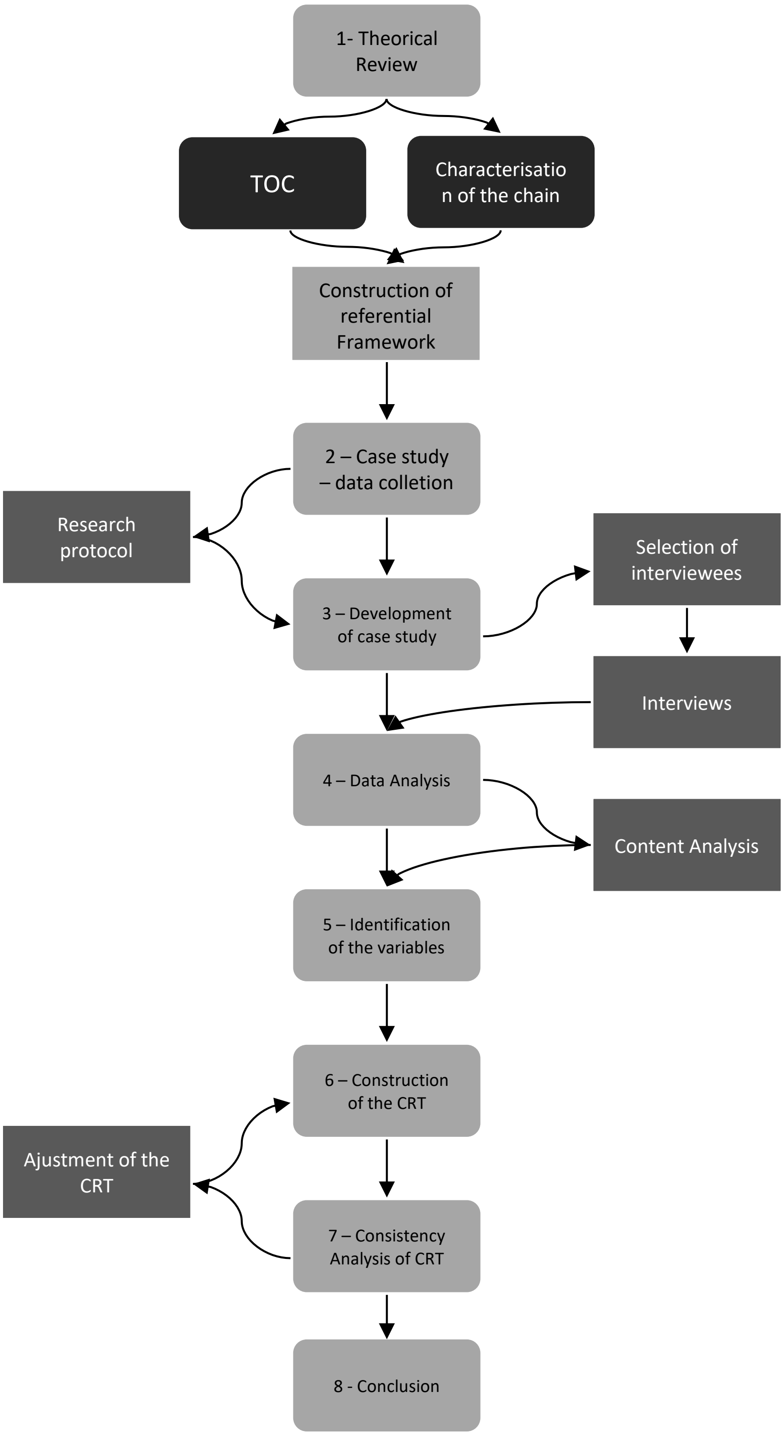

Figure 2. Stages of the research method
Source: The authors themselves.

3.2 Development of the case study- Data collection

Interrelationships and the involvement of multiple actors characterize the soybean supply chain. To gather valuable information regarding this complex context, interviews were deemed the most suitable data collection method (Garrett and Rausch, 2016)We developed semi-structured interviews to capture respondents' perceptions of sustainability within the soybean supply chain. These interviews comprised open-ended questions presented in the Supplementary Information (Table S1). To ensure a comprehensive coverage of sustainability pillars (social, environmental, and economic), we aligned our interview distribution with the Triple Bottom Line (TBL) framework, as delineated by Silva *et al.* (2023).

To ensure the selection of relevant participants with knowledge of the soybean supply chain in South Brazil, the selection criteria considered both the scope and relationship of the potential interviewees with other chain members. Interviews were conducted online between December 2021 and February 2022. Confidentiality and anonymity were ensured for all respondents to minimize the potential for bias (Nederhof, 1985). All participants signed the Participant Informed Consent. Eleven full-length interviews were recorded and transcribed, ranging from 30 to 60 minutes (mean 48 minutes), and more details are in Table 1. It is worth noting that a pilot interview was conducted with a supply chain expert to validate the interview script. The sample size was determined by the saturation effect, which is commonly used in qualitative research, according to Fusch and Ness (2015). Marshall *et al.* (2013), state that the saturation effect, which is frequently employed in qualitative research, was utilized to calculate the sample size. The soybean supply chain study interviewees were chosen based on criteria considering the chain's complexity, diversity, and interactions with many stakeholders. The interviews were conducted using the 'snowball' technique, which enabled the identification of key members across different stakeholder groups (Noy, 2008).

Expert panels were organized based on the insights obtained from the interviews. The panel of experts is essential in validating the current reality tree, providing a critical assessment based on specialized knowledge. The panels were conducted through the Teams tool for videoconferences between March 2022 and June 2022, for approximately 2 hours each. The study team conducted seven panels, summarized in Table 1, and selected all specialists based on their expertise in the soybean supply chain in South Brazil. The panel included two experts in agribusiness, sustainability, and soybeans; one previously interviewed specialist from the soybean supply chain; one new specialist from the soybean supply chain; two experts in thinking process research; and one expert in plant stress physiology. The overarching goal of these expert panels was to assess and validate the CRT, ensuring its refinement. This comprehensive approach aimed to enhance the CRT's reliability and applicability within the soybean supply chain context in South Brazil.

Table 1 - Information from the interviewees selected in this research and specialists

	Time experience	Professional Qualifications	Activity in the Typical Brazilian soybean supply chain and area of Expertise	Age	Gender
P1	6 years	Soybean oil preparation and extraction	Manufacturers	35	Male
P2	20 years	Agricultural machinery	Input Providers	55	Male
P3	30 years	Soybean Producers Association	Cooperatives	42	Male
P4	10 years	Agribusiness company	connection between members	37	Female
P5	28 years	Soybean brokerage	connection between members	60	Male
P6	14 years	Research and Development	Research & Tech Assist	56	Male
P7	14 years	Soybean producing company	Producers	40	Male
P8	2 years	Soybean oil packaging and sales company for the national market.	Manufacturers	36	Male
P9	10 years	Company production, multiplication, and processing of soybean seeds	Input Providers	42	Male
P10	9 years	Agricultural Audit, Analysis, Certification, and Monitoring Company.	Research & Tech Assist	38	Male
P11	8 years	A chemical fertilizer production	Input Providers	39	Male

	Time experience	Professional Qualifications	Activity in the Typical Brazilian soybean supply chain and area of Expertise	Age	Gender
		company			
EP1	24 years	Ph.D. in Management Science. (LANCASTER).	Thinking Process	53	Male
EP2	15 years	Ph.D. in Industrial Engineering (COPPE/UFRJ)	Thinking Process	53	Male
EP3	7 years	Ph.D. in Industrial Engineering (UFRGS)	Agroindustry and Sustainability	35	Male
EP4	6 years	Ph.D. in Industrial Engineering (UFRGS)	Thinking Process and Agroindustry	36	Male
EP5	20 years	Grain broker	Intermediation between farmers and cooperatives with traders	55	Male
EP6	10 years	Agribusiness Manager	Rural finance for medium and large farmers		
EP7	5 years	Ph.D. candidate in Plant Biology	Stress physiology in plants	35	Female

Source: The authors themselves.

3.3 Data analysis

The transcripts of the interviews underwent a rigorous and systematic analysis using Content Analysis (Bardin, 2011) to investigate the content objectively. Coding was carried out using a Microsoft Office Excel spreadsheet, and NVivo qualitative data analysis software was utilized to identify plausible relationships between themes. The analysis process involved the following steps: (1) inserting interviews; (2) creating analysis categories based on factors identified in the literature; (3) analyzing the interviews and classifying excerpts; (4) generating a spreadsheet report containing excerpts from the interviews for further identification of variables.

The analytical categories were formulated by drawing upon the constructs of organization, dynamics, and problems/constraints. This deliberate construction was guided by the need for their appropriateness, ensuring not only the categories' relevance to the analyzed material but also their alignment with the theoretical (Bardin, 2011). The content analysis helped identify the variables and explore the undesirable effects and causes of developing sustainability for the soybean supply chain.

To ensure the accuracy and rigor of the data analysis, the first author conducted several rounds of reading the transcribed texts, identifying relevant excerpts, and coding data. Subsequently, the second author reviewed all the codings made by the first author, and the interview excerpts were entered into the NVivo software. The CRT was developed, the excerpts were read, and the variables used in the undesirable effects and causes were identified. Constructions, relevant excerpts from the interviews, and references presenting the expressed excerpts were included in a matrix format (Chiffoleau and Dourian, 2020) to facilitate in-depth data analysis and visualization (Miles *et al.*, 2018). The CRT was constructed by linking the undesirable effects and their basic causes, following the steps outlined for this process Table 2 (Noreen *et al.*, 1996). The consistency of the CRT was assessed through analysis through the expert panels. Any doubts or uncertainties expressed by the experts regarding the causes and/or undesirable effects were addressed using relevant literature excerpts.

Table 2 - Steps to build the CRT

Steps	Activities
01	Make a list of five to ten undesirable effects related to the situation
02	If you find a connection between two or more undesirable effects, connect to this group and check whether there is a proviso regarding clarity between them. If there is no proviso, choose an effect randomly and carry on to
03	Connect the other undesirable effects to the result of the previous step, making provisos for each entity and connecting with arrows throughout the process
04	Read the tree from the bottom up, again presenting the provisos of clarity of each arrow and entity, carrying out the necessary corrections

05	Ask yourself whether the tree reflects your intuition about this area. If not, look at each arrow to discover additional provisos
06	Do not hesitate to expand the CRT to connect other undesirable effects
07	Re-examine the undesirable effects, identifying the entities in the tree that are intrinsically negative, even if the entity is not part of the original list, or you have to expand the CRT upwards
08	Eliminate from the CRT any entity that is not necessary to connect all the undesirable effects
09	Show the tree to someone who can help you bring it to the surface and challenge the assumptions found there
10	Examine all the points of entry to the CRT and decide which you want to attack. Choose those that contribute most to the existence of undesirable effects

Source: adapted from Noreen *et al.* (1996).

The systematic analysis conducted in this study involved the identification of all the basic causes present in the complex soybean supply chains, with a specific focus on those causes that exert influence on the non-sustainability aspects of the system. These causes were then clustered together based on their similarities. Expert researchers in systems thinking evaluated the developed CRT and subsequently analyzed the identified basic causes to pinpoint the leverage points (Serrano *et al.*, 2019). The analysis employed two forms to identify these points: reviewing the literature and carefully examining interview responses. Firstly, the leverage points were determined based on their significance in achieving the goal of sustainability in soybean supply chains.

We focused on the systemic avenues constructed based on the identified leverage points in the second analysis phase. These avenues were the foundational pillars that facilitated the implementation of planned actions. Various variables that widely influence the entire supply chain were identified within these avenues. Modifying these variables makes it possible to drive sustainable bean supply chains (Serrano *et al.*, 2018).

We group undesirable effects, resulting in cause-effect-cause relationship segments. The primary undesirable effects demonstrate that managing the soybean supply chain can limit sustainability. The system identifies the basic causes, which form the foundation for undesirable effects and help minimize the primary effect. Finally, regarding the facts of life, we observed that these causes exist due to contextual factors. The CRT structure presents the undesirable effects, basic facts of life, and primary effects in numbered boxes, making them easy to identify and connect. The same box numbers will be used within parentheses to reference effects throughout the text.

4 RESULTS

4.1 Interview results

Initially, At the outset of this study, segments of interview excerpts were extracted and linked to each pillar of sustainability. The study kept the respondents' answers unaltered and maintained the confidentiality of the interviewees' identities. Table 3 illustrates selected raw excerpts and their corresponding Undesirable Effects (UDEs). The extracted sentences faithfully represent the interviewees' views and serve as valuable references for this research.

Table 3 - Excerpts from interviews

TBL	Excerpt from the interview	UDEs
Social	There is a series of mandatory training for each role, so within the dimension of the role, we have a list of mandatory training that that person must have. (**Interviewee 1)** Yes, we like that, we like that, we have the training on safety at work, which we give them mandatory. For everyone who has the need (**Interviewee 4)** So the company helped a lot, gave school supplies, and gave incentives. We closed a partnership with Senac, with SEBRAE, and with all these bodies, right? From the system, and it was pretty cool. Many people stayed and are there today, giving their best. People who	There is little incentive to study for employees (13)

TBL	Excerpt from the interview	UDEs
	enjoyed studying and want to go to college now (**Interviewee 11)**	
Economic	Eh, and the agricultural activity plants irrigation that in the dry season, no one will pick up a pivot and turn it on in the rainy season. It's going to waste energy, it's going to waste water (**Interviewee 3)** For example, in this crop that started with rains here, maybe soybeans with twenty percent moisture came very wet soybeans. No, then you will have to go to the dryer and lower it a little to put it inside the silo because the soybean that is too wet can get clogged (**Interviewee 4)** Because it's too expensive, you know today to turn a diesel pivot is very expensive, electric pivot too, energy is costly. (**Interviewee 9)**	Companies use more energy (34)
Environmental	With the research and the work done over the years, research work, and technical assistance, much knowledge was taken to the farmer and the importance of preserving it. (**Interviewee 10)** Agricultural pesticides to have continuously more productive (**Interviewee 8)** He knows he can't spill poison on the ground (**Interviewee 2)**	There is an increase in the consumption of natural resources (5)

Source: The authors themselves.

Initially, the team listed the undesirable effects and the basic causes of CRT at the end of the transcripts. Table 4 shows an extract of these effects and the related numbering. Notably, the team initially listed 127 effects, and as they built the CRT, they increased the number to 211 (presented in the Supplementary Information Figure S1, Figure S2, and Figure S3). In addition, the Supplementary Information includes a list of connectors (Table S2) utilized to establish links between undesirable effects that are spatially distant from each other. Numbers accompanied by * indicate those that emerged after the authors drafted the CRT (Current Reality Tree) or during expert panel deliberations.

Table 4 - Extracts of the undesirable effects

#	Description
1	Long-term relationships in the chain are not maintained
2	There is an increase in the prioritization of soybeans for export
3	There are changes in weather patterns
4	Chain members do not use clean or renewable energy technologies
5	There is an increase in the consumption of natural resources
6	Used more defensively than allowed

Source: The authors themselves.

The development of the CRT for the soybean supply chain started during the expert panel sessions after this list of consequences. Researchers thoroughly examined the CRT, which also examined its coherence and suggested any necessary modifications. The following section will show the improved version of the CRT, incorporating the improvements made during the expert panel talks.

4.2 The CRT of sustainability in the soybean supply chain

Figure 3 presents the Current Reality Tree (CRT) constructed based on the data analysis. The CRT was divided into three segments, Figures 3a, 3b, and 3c, according to the three dimensions of sustainability: social, environmental, and economic. In Figure 3a, the primary undesirable effect identified is that “the soybean supply chain is less socially sustainable”. Figure 3b focuses on the environmental dimension, with the primary undesirable effect being “the soybean production chain is less environmentally sustainable”. Figure 3c, contemplates the economic dimension, ending with the primary undesirable effect “the soybean production chain is less economically sustainable”.

Each element of the CRT was represented with a color to facilitate its interpretation: Facts of life (pink) represent conditions that are widely accepted or difficult to change in the short term. Undesirable effects (white) are negative consequences observed in the system. Broader undesirable effects (yellow) indicate impacts with greater scope or intensity. Basic causes (green) indicate the fundamental elements that give rise to the undesirable effects. Logical connectors:

used to demonstrate the cause-and-effect relationships between the different elements of the tree.

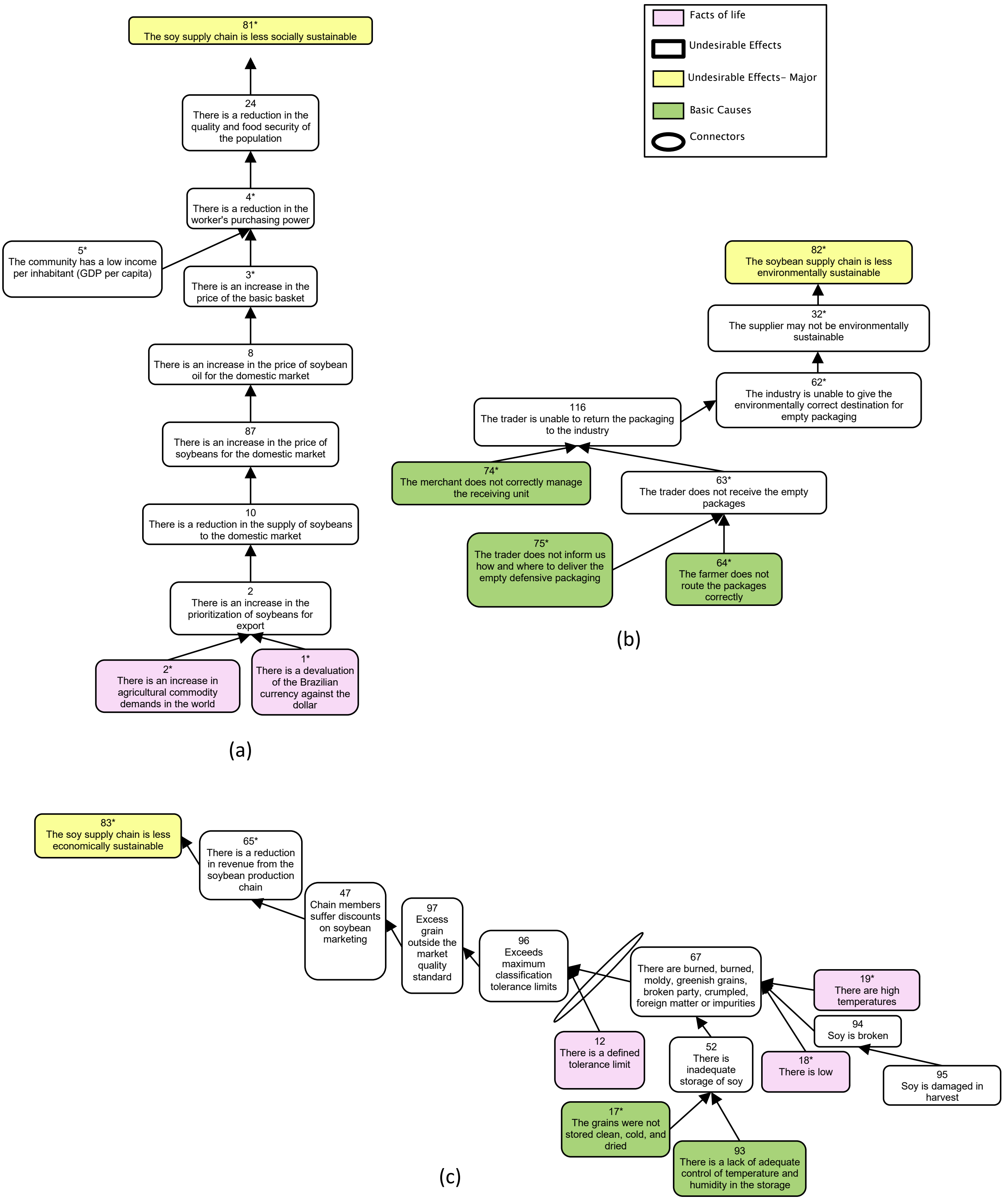

Figure 3. CRT segments of the South Brazilian soybean sustainable
Source: The authors themselves.

By reading the first segment (related to primary UDE “the soy supply chain is less socially sustainable) of the CRT upwards in Figure 3a, it becomes apparent that the devaluation of the

Brazilian currency when compared to the dollar (1*) and the increase in demand for agricultural commodities worldwide (2*) are basic causes and facts of life. These two causes lead to the undesirable effect of increased prioritization of soybeans for export (2), reducing soybean supply for the domestic market (10). Consequently, this reduction leads to an increase in the market price of soybeans (87), which generates a corresponding increase in the price of soybean oil for the domestic market (8), leading to an increase in the price of the basic food basket (3*) and a reduction in the purchasing power of the worker (4*).

The segment illustrated in Figure 3b highlights another primary UDE: "The soybean supply chain is less environmentally sustainable" (82*). This undesirable effect implies that the supply chain must undertake actions that account for their environmental impact. In this section of the CRT, the basic causes are the failure of farmers to dispose of packages correctly (64*) and the traders' failure to provide information on how and where to deliver empty pesticide packages (75*). These two basic causes result in the trader not receiving empty packages (63*). This effect (63*) and the trader's inability to manage the receiving unit correctly (74*) generate the effect that the trader cannot return the packages to the industry (116). Consequently, the industry cannot provide an environmentally responsible destination for empty packaging, which leads to suppliers that may not be environmentally sustainable (32*), ultimately contributing to the soybean supply chain's environmental unsustainability (82*).

The third segment of the CRT (related to primary UDE “the soy supply chain is less environmentally), as shown in Figure 3c, demonstrates that damaged soybean collars (95) result in broken soybeans (95). This cause (94), along with natural factors such as high temperatures (19*) and low relative humidity (19*), lead to scorched, burnt, molded, green, broken, dented, contaminated with foreign matter, or impure grains (67). Furthermore, the inadequate storage of soybeans (52) is caused by grains not being stored clean, and dry (17*) and the lack of adequate temperature and humidity control during storage (93), resulting in the same effect (67). The cause (67) combined with the basic cause leads to an excess of grains outside the market quality standard (96), resulting in discounts for the chain members on soybean trade (47). This, in turn, generates a reduction in revenue for the soybean production chain (65*), ultimately rendering the soybean supply chain less economically sustainable (80*).

As seen, it was divided into three figures to facilitate the identification and discussion of the CRT. The first figure illustrates the undesirable effects associated with social issues, the second with environmental problems, and the third with economic issues. Many causes that appear in one sustainability pillar are also causing for another, such as players with less bargaining power receiving a smaller share of the added value (77*) (Social), which is also a cause in the economic pillar. Another example is the reduction in soybean supply in the domestic market (10), included in the social pillar, but its undesirable effect, reduction in productivity (42*), is presented in the economic pillar.

When constructing the CRT, it becomes evident that the components are systematically interconnected and cannot be comprehended or analyzed independently, as the effects identified in a certain chain segment impact other (Librelato *et al.*, 2014). Hence, the three figures are linked, and the undesirable effects in the cause-effect-cause relationship may appear in another figure or pillar. Therefore, the three figures are interdependent, revealing the entire CRT when combined. Through the CRT's exposition, it was feasible to recognize the fundamental causes that trigger the primary undesirable effects. Furthermore, analyzing the cause-and-effect relationships made it possible to describe the problem that needs to be addressed.

The soybean supply chain's lack of sustainability is complex due to various interactive and rapidly changing constraints, compounded by several tight constraints that operate based on optimal local guidelines (Cox III and Schleier, 2013). The difficulty of resolving complex problems often leads to financial losses and prevents continuous improvement because the basic cause is often unknown, and only superficial symptoms are addressed, which limits significant improvements despite significant investments (Walker and Cox, 2006). The Theory of Constraints (TOC) addresses this issue by providing a simple and easy-to-apply method for structuring complex problems, enabling the discovery of their underlying causes with high clarity of results (Mabin and Balderstone, 2020). Furthermore, based on the analysis of cause-and-effect relations, it was possible to characterize the problem to be solved.

4.3 Categorizing Basic causes: An undesirable effects (UDEs) Analysis

Analyzing this CRT made it possible to identify the basic causes of the UDEs (Table 5). The underlying causes were categorized based on their similarity, resulting in seven categories: Facts of Life, Architecture and Chain Management, Actors and Operations, Environmental Management, Social Aspects, and Bureaucracy. The Facts of Life refer to undesirable effects due to the context.

The causes considered as facts of life are basic assumptions considered true and unchangeable in the system under study (Dettmer, 1998). Architecture and Chain Management are undesirable effects related to management and strategic objectives that optimize the supply chains. Actors and Operations are undesirable effects related to the operation of supply chain actors (traders, financiers, producers, manufacturers, and cooperatives) operating and supply chain management. Environmental Management is undesirable effects on production or operations management whit natural resources. Social Aspects are associated with employees' well-being and society. Bureaucracy is related to mandatory documentation. As the causes are interrelated, they can be present in more than one class, but we chose only one of them.

Table 5 - Basic causes of sustainability CRT in the soybean supply chain in southern Brazil

#	Undesirable effect	
110	Farmer did not refinance the debts of previous harvests	Actors and Operations
17*	Grains did not stored clean, cold, and dried	
63	Chain members lack awareness in energy usage	
74*	The merchant does not correctly manage the receiving unit	
93	There is a lack of adequate control of temperature and humidity in the storage	
64*	Farmer does not route the packages correctly	
106	There is a physical distance between the consumer and the producer	Architecture and Chain Management
107	There are many intermediaries along the chain	
29	There is a lack of exchange of information between farmers	
37*	There is no correct monitoring of the entire soybean production chain	
75*	The trader does not inform us how and where to deliver the empty defensive packaging.	
1	Long-term relationships are not maintained in the chain	
125	The producer does not have all the state documentation of the land	Bureaucracy
126	The producer has no rural declaration in the IR	
43*	The producer owns a rural property	
64	The producer does not have a Rural Environmental Registry	
122	The producer has environmental fines	Environmental Management
123	The producer has his land in proximity or overlapping with preservation areas	
18	Lack of management of household oil waste	
19	Lack of management of lubricating oil residue on farms	
45	Chain members do not store rainwater	
56	There is an absence (or incorrect) initial diagnosis of soil	
6	Defensive agricultural practices exceed permitted levels	
67*	No-tillage is not carried out	
11	There is no correct biological control of pests	
69	Chain members do not have adequate effluent treatment	
68*	Monoculture is practiced	
86	There is an increase in the agricultural frontier	
49*	The government does not invest in combating deforestation	
4	Chain members do not use clean or renewable energy technologies	
2*	There is an increase in agricultural commodity demands in the world	Facts of Life
1*	There is a devaluation of the Brazilian currency against the dollar	
23	There is a shortage of rain	
19*	There are high temperatures	
18*	There is low relative humidity	
81*	There is a reduction in the global supply of soybeans	
72*	There is a health uncertainty (E.g., the COVID-19 pandemic)	
71*	There is international political uncertainty (E.g.: Russia vs. Ukraine War)	
70*	There is national political instability	
23*	This low marketing price of soybeans	
40*	The amount paid for soybean seeds is high	

69*	There are excesses of rain	
98	Supplies are lacking for agricultural machinery production	
78*	There is an increase in the cost of energy	
117	There are no commercial or societal pressures for sustainable practices	
16	Discrimination of race, color, ethnicity, and gender occurs.	
16*	The community does not understand the importance of qualifying	
17	If the links in the chain ignore the quality of life of employees	
27	Chain members do not hire Person with a Disability	
59	There is employee churn	Social Aspects
65	It is not promoted by investment companies prevention of risks in occupational safety and health	
88	Jail members want to pay less for labor	
90	There is little community involvement among the members of the	
91	The company does not provide courses and training (inside and outside the company)	

Figure 4 presents the seven categories of groupings, divided spatially among the three pillars of sustainability. The size of each circle corresponds to the number of basic causes present in that group. The location of each circle within the triangle (environmental, social, and economic) indicates which pillar of sustainability it belongs to, based on the divisions of the CRT.

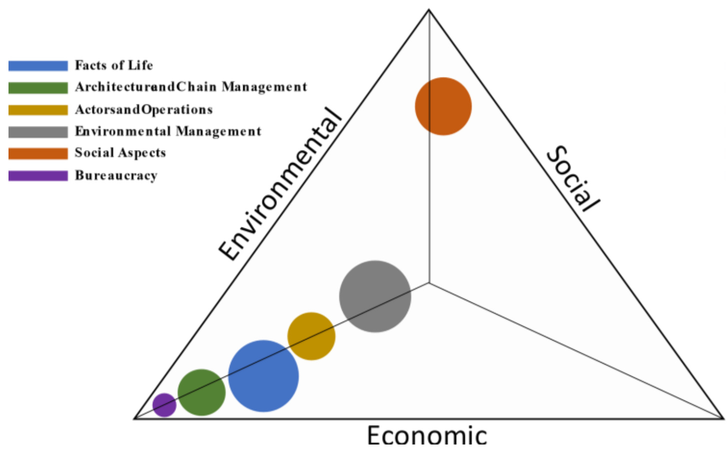

Figure 4 - Cluster representation of basic causes
Source: The authors themselves.

This study observed that the economic pillar has 21 basic causes, the environmental pillar has 20 basic causes, and the social pillar has 9 basic causes. Hence, based on the perspectives of the interviewees, each pillar contributes to adverse effects on sustainability. Additionally, it was observed that the environmental and economic pillars exert a more pronounced impact on sustainability compared to the social pillar, which holds a relatively lesser influence.

4.4 Exploring Leverage Points: Structure and Implications in the supply chain

The CRT made it easier to deepen and expand the understanding of the system. The knowledge derived from the system's structure includes leverage points and their ramifications, represented by the following types of relationships: If a leverage point exists, it implies an action. The leverage points were identified by examining all basic causes with immediate possibilities for action. Table 6 succinctly outlines the identified leverage points.

Table 6 - Leverage analysis

UDEs	#	Leverage points	TBL	%
90	1	There is little community involvement of chain members	Social	5.16
65	2	Companies do not promote investment in risk prevention in occupational health and safety	Social	3.75
107	3	There are many intermediaries along the chain	Economic	28.64
29	4	There is a lack of exchange of information between farmers	Economic	2.35
1	5	Long-term relationships are not maintained in the chain	Economic	40.85
6	6	Defensive agricultural practices exceed permitted levels	Environmental	30.05
4	7	Chain members do not use clean or renewable energy technologies	Environmental	4.23
45	8	Chain members do not store rainwater	Environmental	1.88

Leverage points 1 and 2, which are related to little community involvement of chain members and companies' lack of investment in risk prevention in occupational health and safety, are part of the social aspects of the TBL. Leverage point 1 corresponds to an issue related to community involvement in the supply chain. According to Chianu *et al.* (2009), social aspects, such as large-scale community involvement, capacity building, and training for the community, were among the main drivers behind the successful promotion of soybeans in Nigeria. On the other hand, leverage point 2 is a basic cause directly linked to the chain's employees. Bellochio et al (2022), point out that companies should consider the organization's context and involve workers in planning, supporting, evaluating, and outlining improvements to prevent risks in occupational health and safety.

The economic aspects of TBL are associated with leverage points 3 (the presence of numerous intermediaries in the chain), 4 (inadequate exchange of information among farmers), and 5 (the absence of long-term relationships in the chain). Leverage point 3 pertains to the problem of having many intermediaries in the supply chain. According to Afrianto *et al.* (2020), blockchain technology can minimize the problems caused by intermediaries by improving traceability and information exchange. Leverage point 4 directly links to the exchange of information among farmers. Putra *et al.* (2019) state that stronger farmer relationships facilitate information exchange. Leverage point 5 corresponds to the importance of long-term relationships in the supply chain (Jia *et al.*, 2020; Williams *et al.*, 2017) state that trust is critical for maintaining long-term relationships, which significantly affect risk perceptions and the willingness of chain members to cut costs.

The leverage points 6 (Defensive agricultural practices exceed permitted levels), 7 (Chain members do not use clean or renewable energy technologies), and 8 (Chain members do not store rainwater) correspond to the environmental pillar of sustainability. Leverage point 6 can be addressed by increasing awareness, implementing inspection, and adopting alternative pest control practices (Lacerda *et al.*, 2010; Mabin and Balderstone, 2003). Regarding leverage point 7, Jha and Tripathy (2017) suggest developing policies that encourage the adoption of clean and renewable energy technologies by chain members. As mentioned in leverage point 8, rainwater storage is crucial for soil irrigation in drought-prone areas and should be prioritized, especially in arid regions (Rattis *et al.*, 2021).

In summary, addressing the basic causes, particularly the leverage points, should be a key strategy for improving sustainability in soybean supply chains. The fifth column of Table 6 presents the percentages corresponding to the undesirable effects that resolving each listed undesirable would eliminate. The Current Reality Tree (CRT) reveals a hierarchy of undesirable effects with unequal impacts on the chain. The analysis directly impacts efficiency and overall performance by stating, "Long-term relationships are not maintained in the chain" (40.85%). Without long-term relationships, stability and cooperation are hindered, which reduces the sustainability of the soybean supply chain.

The use of it more defensively than allowed (30.05%) demonstrates environmental and regulatory weaknesses. The absence of sustainable and preventive practices puts legal compliance and the longevity of the chain at risk. The presence of many intermediaries along the chain (28.64%) suggests a fragmented and inefficient chain, increasing costs and reducing profits for end producers.

Different stakeholders in the soybean supply chain must take targeted actions based on the identified leverage points to improve sustainability. Policymakers should promote regulatory frameworks that encourage community involvement, occupational health and safety investments, and the adoption of clean energy technologies. Supply chain managers should work toward reducing intermediaries by implementing transparent trade mechanisms, such as blockchain, to enhance traceability and trust. Farmers and producer organizations should strengthen information exchange and collaboration to build long-term relationships that improve efficiency and risk management. Additionally, companies should prioritize sustainable practices, including integrated pest management, rainwater harvesting, and renewable energy adoption, to mitigate environmental risks. By addressing these key leverage points, stakeholders can collectively enhance the sustainability of the soybean supply chain.

5 DISCUSSION

The CRT highlights the detrimental effects that impede TBL sustainability, thus hindering the proper execution of sustainability in the soybean supply chain. The clusters Environmental Management and Facts of Life have the most undesirable effects, with basic causes that cannot be changed in the system under study since they are basic assumptions considered true without the possibility of change. The basic causes of the Environmental Management cluster reveal the fragility of managing natural resources. According to Maranhão *et al.* (2019) cropping systems' high productivity and profitability are an incentive for expanding agricultural frontiers, which has been associated with the widespread degradation of Brazilian ecosystems (Fuchs *et al.*, 2019; Mercio *et al.*, 2021). Harvey (2021) highlights the importance of enhancing environmental protection schemes in Brazil, and the international community must encourage the Brazilian government to increase its efforts in this regard.

Based on the analysis of the complete CRT, it is evident that there is a lack of inputs for agricultural processing to occur, marked by leverage point 58. External factors contribute to this issue, such as blockades and restrictions on the movement of goods and materials caused by the COVID-19 pandemic, which has led to reduced food production due to a lack of inputs, as noted by Fan *et al.* (2020). Moreover, amidst the conflict in Ukraine, nations found themselves compelled to adjust by importing commodities from other countries to sustain agricultural processing, a topic explored in Jagtap *et al.* (2022).

The conflict of interests related to the soybean supply chain, which prioritizes soybean for export (2), is identified as a social aspect. This conclusion is supported by Richards *et al.* (2012), who state that the devaluation of the real against the US dollar drove the expansion of soybean exports by Brazil, reducing the local supply of soybean and increasing the price of soybean and its products in Brazil. Conversely, Cattelan and Dall'Agnol (2018) found that municipalities that produce soybean consistently have a higher Human Development Index (HDI) than those that do not.

These distinct characteristics imply that the sustainability of the soybean supply chain in southern Brazil possesses unique aspects that must be considered in any analysis (Cattelan and Dall'Agnol, 2018). Moreover, the literature suggests that the issues highlighted by the interviewees are indeed prevalent in the soybean supply chain (Richards *et al.*, 2012).

6 CONCLUSION

This article aimed to structure the undesirable effects and underlying causes that lead to the non-sustainability of the soybean supply chain in southern Brazil. The CRT tool was employed to comprehend the issues faced by this chain, focusing on answering the question of "What to change?" The underlying causes and undesirable effects were then arranged in cause-effect-cause relationships until the most significant impact was identified, namely, the "Soybean supply chain is not sustainable."

The use of the Current Reality Tree (CRT), discussing its findings with the literature on sustainable development and soybean production in southern Brazil, validated the tool's efficacy in identifying the basic causes and unintended consequences that affect sustainable supply chains in various contexts. This article contributes to performing a similar analysis of any other food supply chain and identifying the underlying causes and undesirable effects that affect its sustainability. This article also provides results for future research and interventions to achieve sustainable soybean production in southern Brazil by segmenting the problem and structuring actions to improve sustainability throughout the chain. Since no comparable research has addressed this area, this work stands out for its uniqueness and significance in advancing understanding and promoting sustainability in the soybean supply chain.

It is important to note that the elements used to create the CRT were selected based on a triangulation of the interviewees' perspectives with the relevant literature. The CRT was then thoroughly analyzed and discussed by experts, who provided valuable insights into understanding the causes and/or undesirable effects identified in the study. This process ensures that the CRT accurately captures the complex reality of the soybean supply chain in southern Brazil and that the resulting analysis is rigorous and well-informed.

As a practical contribution, the soybean supply chain contributes leverage points. Actionable steps for some stakeholders, for example, policymakers, must promote initiatives to increase community involvement of chain members through policies and programs that encourage collaboration. Establish regulations requiring companies to invest in risk prevention for occupational health and safety. Implement policies to reduce the number of intermediaries along the supply chain, increasing efficiency and fairness. Encourage policies that foster long-term relationships between supply chain members to improve stability and cooperation. Develop incentives and regulations to promote clean or renewable energy technologies. Support water conservation efforts by providing incentives for rainwater storage among supply chain members.

The farmers must participate in cooperative or local groups to improve information exchange and strengthen collaboration. Engage in training and workshops on occupational health and safety measures to reduce risks. Build networks to establish long-term relationships within the supply chain for better trade conditions and stability. Adopt clean and renewable energy technologies to reduce environmental impact and operational costs. Implement rainwater storage solutions to improve water conservation and resilience to climate variability.

The supply chain managers must establish transparent communication channels to facilitate information exchange between farmers and stakeholders. Reduce reliance on intermediaries by improving logistics and direct trade strategies. Foster business relationships that emphasize long-term cooperation rather than short-term gains. Invest in sustainable energy alternatives for operational processes. Encourage best practices in water conservation by implementing rainwater storage solutions at various stages of the supply chain.

This study's academic contribution is to show the potential of CRT to analyze the sustainability of the food supply chain. With regard to generalizing how to perform the analysis, this can be applied to other sectors. The study acknowledges the limitation of using the CRT tool as the sole instrument to identify the underlying causes and undesirable effects of the soybean supply chain's non-sustainability. This limitation lies in adopting qualitative study, which does not permit statistical generalization. Consequently, the study does not allow for the extrapolation of findings to other populations or production chains. While the tool helps to identify the undesirable effects, it may not be sufficient to address all the complex and interconnected issues in the chain. Another limitation of this study is its primary reliance on interviews and expert panels, which do not delve deeply into the perspectives of marginalized stakeholders, such as small-scale farmers or laborers. This may cause an incomplete understanding of the broader social dynamics within the soybean supply chain. Therefore, the study suggests further research and other systemic techniques to complement the analysis and generate a more comprehensive understanding of the problem.

Some possible future studies related to the analysis of the soybean supply chain in southern Brazil include implementing the proposed actions identified in the leverage points using other systemic techniques for sustainability analysis and validating the elements identified in this study through a Survey with supply chain members.

Could adopt a mixed-methods approach, combining qualitative insights with quantitative data to enhance the generalizability and analytical depth of the findings. In particular, integrating financial metrics and operational data would enable a more comprehensive evaluation of sustainability impacts across the soybean supply chain. Such an approach would support more robust analyses and contribute to a better understanding of the relationship between sustainability challenges and measurable business outcomes. Additionally, researchers could conduct studies to analyze the potential impacts of proposed solutions on other sectors and explore potential trade-offs between economic, social, and environmental sustainability goals in the soybean supply chain. Finally, researchers could investigate the role of policy interventions and governance mechanisms in promoting sustainable practices within the soybean supply chain in southern Brazil.

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