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Industry 4.0 and Sustainability Integration in the Supply Chains of Micro, Small, and Medium Enterprises through People, Process, and Technology within the Triple Bottom Line Perspective

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Abstract: This study fills a crucial gap in the research on Micro, Small, and Medium Enterprises (MSMEs), with the main objective of proposing a framework to support the integration of Industry 4.0 (I4.0) and sustainability into the supply chains of MSMEs. This integration is accomplished by people, process, and technology (PPT) mechanisms, all while adopting the triple bottom line (TBL) perspective. A mixed-method approach was employed for this study, which included a scoping review of 147 publications, expert panels, focus groups, and a survey with 55 valid responses. The findings identified 32 key indicators linked to the primary barriers and enablers of I4.0 and sustainability integration (S-I4.0) in MSMEs' supply chains. This study also highlighted the dominant barriers and enablers within the PPT mechanisms and TBL dimensions, and their causal relationships and influences. The results were synthesized into a novel S-I4.0 framework, separately applied to Micro and Small Enterprises (MSEs) and Medium Enterprises (MEs) due to company size-related variations. This study offers valuable insights for academics and provides practical guidelines to assist MSMEs in integrating I4.0 and sustainability into their supply chains. An important contribution concerns to the need to treat MSEs and MEs differently. These research results provide relevant and novel guidance for MSEs and MEs to accelerate the S-I4.0 adoption process, with an immediate impact on their supply chains.

Keywords: digital transformation; Industry 5.0; operations management; developing countries; empirical research

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1. Introduction

Barriers and enablers for the sustainable implementation of Industry 4.0 (I4.0) in supply chains have been increasingly discussed in both academia and industry [1,2]. Various industrial sectors and their respective supply chains have been impacted by I4.0, with new challenges for their organizations worldwide [3,4], influencing existing business models and strategies [5,6]. The digital transformation resulting from the evolution of the I4.0 concept is directly related to the future of industries globally in the long term, being a fundamental factor for their competitiveness since the process of integrating these technologies needs to overcome short-term management objectives, in addition to overcoming the complexity of integration challenges sustainably without negatively impacting organizational performance [7,8]. The impacts of adopting new tools and technologies go beyond the limits of the industries involved; society in general must be involved from the initial stages so that adoption and management can be carried out responsibly [9]. The challenge of integrating new technologies with other sophisticated and

well-established technologies in industries is inevitable, such as with the implications of big data and predictive analytics [10], with transformative impacts on industrial processes globally, under penalty of isolation from the global productive scenario for those industries that do not adhere [7,11].

Therefore, the I4.0 journey of organizations should contemplate a sustainability perspective [12], thus facilitating the search for excellence in the face of the changes imposed by the digital transformations underway in global economies [13]. There has been significant growth in corporations and the practices applied in their supply chains based on the triple bottom line (TBL) concept of sustainability [14] or similar concepts, such as profit, planet, and people [15]. There is growing interest in integrating the TBL dimensions of sustainability with I4.0, such as with the employment of the circular economy [16], where the effective integration of I4.0 technologies and circular economy techniques allows organizations to act sustainably based on TBL concepts [17,18]. The synergy between I4.0 technologies and circular economy techniques leverages organizational performance and strengthens sustainable practices [19]. The sustainable application of I4.0 technologies promotes results aimed at an organization's operational efficiency, among other benefits directly related to the organization's sustainable performance [20–22].

Companies of all sizes face major challenges regarding the sustainable integration of I4.0 in operations and supply chain management (OSCM) [12], particularly Micro, Small, and Medium Enterprises (MSMEs) [13,23,24]. MSMEs are central to modern economies for several reasons [25,26], such as their high capacity to generate jobs [27]. Although important and requiring different solutions from those adopted by large companies, MSMEs receive less attention from academics than large enterprises [28]. This research–practice gap needs to be addressed [23,29], as results of empirical studies show that the adoption of I4.0 is considered more difficult and of higher risk by MSMEs [30,31] due to their naturally smaller scope of adoption of technologies compared to larger companies, and to the less relevant role of the integration into sustainable supply chains [32]. Integrating MSMEs into networks can help overcome barriers and encourage the usage of I4.0-related enablers, with direct implications for value chains [33,34]. Barriers are obstacles that make it difficult to carry out activities [35] and enablers enhance actions necessary to increase organizational competitiveness and development processes [36]. Both barriers and enablers can be represented by indicators [37,38], which are viewed as parameters, measures [39,40], quantities, properties of a phenomenon, or substances to which a magnitude can be assigned [41].

Within this context, there is a need to understand the barriers and enablers and develop their indicators associated with integrating I4.0 and sustainability in the supply chains of MSMEs [42,43]. A first attempt in this regard was conducted in [23], investigating the most prominent barriers and enablers and revealing the eight main barriers and eight main enablers for this integration. However, there is still research–practice gap located in the greater difficulty, for MSMEs, in terms of making tangible these barriers and enablers through their indicators, as well as in the understanding of the pertinence of their application in real-life settings [44,45]. Therefore, building upon [23], this paper poses the following first research question (RQ-1):

RQ-1: *What are the critical indicators for the barriers and enablers of integrating I4.0 and sustainability in the real-life settings of MSMEs' supply chains?*

Organizations must be aware of aspects related to the negative impacts of the sustainable adoption of I4.0 and take measures to mitigate them throughout their respective supply chains [46]. Recently, the concept of Industry 5.0 (I5.0) emerged and is paired with with Society 5.0, which emphasizes people within the concept of I4.0, moving towards human-centricity, and includes human-in-loop, which is associated with the idea of a super-intelligent society [47–50]. When we also insert the context of sustainability in I5.0, the role of the industry goes beyond its efficiency and improvement in productivity; in practice, it strengthens the role of the industry as a fundamental contributor to the development

of society [46]. In MSMEs, organizational leaders play a crucial role in deploying I4.0 in their supply chains by fostering environments that encourage knowledge and information sharing [23,51], this being a key point of Society 5.0 that involves society from the guidance of science, technology, and innovation [52], intrinsically associated with the 2030 Agenda of the United Nations [53]. These leaders directly increase their capacity for innovation and, consequently, the sustainable performance of their organizations, even though MSMEs have a greater need to access capital than large corporations [54]. The I5.0 paradigm [55] also recognizes the capacity of industry to become a sustainable foundation of development, first considering the planet's limitations and prioritizing employees' health, a capacity enhanced during the COVID-19 pandemic [56–58]. I5.0 also sheds light on resilience, e.g., [59], which is "the capacity of a supply chain to resist, adapt, or transform in the face of change" [60], being commonly associated as a process by "which resources protect against the negative impact of stressors to produce positive outcomes" [61]. Therefore, I5.0 goes beyond I4.0 with a holistic approach powered by advanced technology and emphasizes human-centricity, sustainability, and resilience [59]. Herein, the perspective of the people, process, and technology (PPT) mechanisms and the TBL dimensions should be considered within the barriers and enablers constructs of the integration of I4.0 and sustainability in the supply chains of MSMEs. However, there is a lack of studies that contemplate barriers and enablers concerning (i) PPT mechanisms [62,63] and (ii) the economic, environmental, and social dimensions from the TBL perspective for MSMEs [64,65]. This research gap is even broader if one considers the context of MSMEs, which have received much less academic attention [23,28,29]. In this regard, MSMEs should have support in identifying the dominant barriers and enablers (the ones with the highest impact levels) for each PPT mechanism and TBL dimension towards seeking the integration of I4.0 and sustainability in their supply chains, which leads to the second research question (RQ-2), as follows:

RQ-2: *What are the dominant barriers and enablers within the PPT mechanisms and TBL dimensions regarding integrating I4.0 and sustainability into the supply chains of MSMEs?*

Barriers and enablers towards this integration were identified and presented in [23], who grouped them into causal and effect categories, revealing variations between Micro and Small enterprises (MSEs) and Medium enterprises (MEs). Notably, they found that the influence of barriers and enablers varies depending on the company's size. This suggests that while MSEs and MEs may encounter similar barriers and enablers, their strategies for addressing these factors may differ, thereby influencing the integration of I4.0 and sustainability in their respective supply chains. This observation underscores the complexity of the integration process and the need for a nuanced understanding of the interplay between various factors. In this context, the third research question (RQ-3) arises:

RQ-3: *What are the causal and effect relationships, as well as the influence among barriers and enablers, regarding the integration of I4.0 and sustainability in the supply chains of MSMEs from a PPT and TBL perspective?*

This question aims to delve deeper into the dynamics of the integration process and provide a more comprehensive framework for MSMEs seeking to integrate I4.0 and sustainability into their supply chains.

Therefore, the goal of this paper is to offer a framework to support the integration of I4.0 and sustainability in the supply chains of MSMEs through people, processes, and technology mechanisms with the TBL perspective. To reach this goal, a mixed-method approach [66] was adopted, combining a scoping review [67] with the use of a panel of experts, a focus group, and a survey [68,69].

To address the three RQs and achieve the stated goal, this paper has five sections, the first of which is this introduction. Section 2 describes the methodology applied. Section 3 brings the critical indicators for the barriers and enablers constructs and then the dominant barriers and enablers within the PPT mechanisms and TBL dimensions regarding the integration of I4.0 and sustainability in the supply chains of MSMEs. Section 4 offers

the proposed framework for I4.0 and sustainability integration. Section 5 presents the conclusions and recommendations for future research.

2. Materials and Methods

A mixed-methods approach [66] was adopted. First, a scoping review revealed critical indicators for the barriers and enablers constructs of the integration of I4.0 and sustainability available in the literature. It was followed by structured interviews with experts/professionals and a focus group aimed towards refining and complementing the critical indicators from an MSME's perspective. The last approach consisted of a survey which aimed to validate the critical indicators obtained in the previous approaches and to reveal the impact levels of the PPT mechanisms and TBL dimensions regarding the barriers and enablers related to I4.0 and sustainability in the supply chains of MSMEs, revealing the dominant ones. Each research approach is described below.

2.1. Scoping Review

The scoping review was conducted according to the five steps offered by [67]: (i) definition of the research problem/questions/goal; (ii) identification of the appropriate documents (e.g., papers and studies); (iii) selection of studies; (iv) data mapping; and (v) grouping and summarization of results. The first step embraces the definition of the research questions and goals, as well as the characterization of the research problem. In this first step, a team of four researchers experienced in I4.0 and sustainability was established, and the research protocol recommended by [70] was adopted. Identifying the relevant studies in the research (next step) consisted of different sub-steps. The selected timeframe was the period between 2015 and 2022. The first screen of the literature was conducted on the 1st of July 2022 and the last screen, aiming to update the sample, was performed in January 2023. The WoS and Scopus databases were chosen to select relevant studies, as they complement each other, cover similar research domains [71], and are relevant for research topics such as OSCM [72]. The combination of main search keywords adopted to retrieve studies in the two databases was: [("Industry 4.0" or "Smart manufacturing") AND ("sustainab*" or "green") AND ("supply chain" or "SCM")]. These search keywords were applied to the titles, abstracts, and keywords of these two databases with no limitation on companies' sizes. The exclusion criteria for the selection of studies consisted of peer-reviewed studies not published in journals and without association with indicators of barriers and enablers associated with I4.0 and sustainability in supply chains.

Figure 1 offers the report of the studies' identification and selection steps, grounded on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (P.R.I.S.M.A.) developed by [73] as it aids in providing review reports in a transparent and objective manner [74,75]. The process started with retrieving 268 studies from Scopus and 391 studies from WoS. One hundred and twenty studies were removed, as they appeared in both databases (duplicated). An additional 365 were also dropped out due to the exclusion criteria applied to abstracts, and 82 were removed from the sample due to their application to full texts. Following [70], a snowball was conducted with backward and forward searches, retrieving an additional 55 studies. The systematization process resulted in the selection of 147 publications, following the three main steps displayed in Figure 1 adapted from [74,75].

Synthesis and content analysis supported the grouping and summarization of the result [70]. Categories were based on the barriers and enablers shown by [23]. The results are reported in Section 3.1 of this paper, together with the ones obtained from the panel of experts/focus groups.

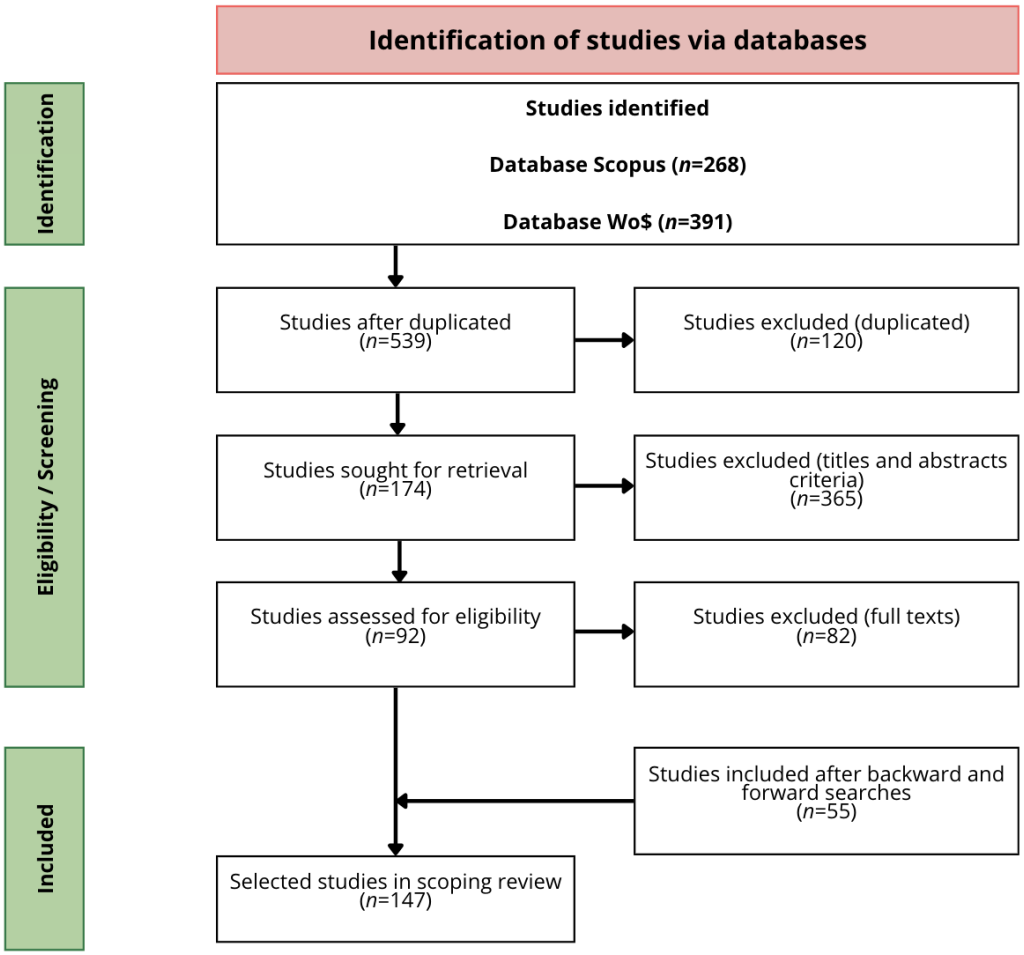

Figure 1. Studies' identification and selection steps grounded on P.R.I.S.M.A. Adapted from [74].

2.2. Panel of Experts and Focus Group

The literature results obtained in the scoping review were next complemented by empirical data obtained from practitioners experienced in both I4.0 and sustainability and in MSMEs, aimed towards embracing an MSME perspective of the critical indicators. Herein, industry experts in the field provided their professional views, understanding, and insights from real-life settings, which were combined and reviewed in subsequent steps/rounds until a consensus was achieved [68], similar to the ones conducted by [23].

The panel was composed of seven practitioners from MSMEs. The process was guided by the indicators obtained in the literature, grouped by barriers and enablers, and it included in its introduction a formal consent term, the main research goals, and a glossary. The researchers provided a brief introduction and explanation of the main concepts, barriers, enablers, and indicators before the panel began improving and aligning the topics' comprehension and avoiding misunderstandings that could affect the results. Besides having the possibility to remove indicators from the list or to move them to other groups, experts were also allowed to provide new indicators relevant to MSMEs if they perceived anything was missing in the initial list. This first round of interaction had an average duration of one and a half hours with each expert.

A second round of interaction with the same seven experts was performed within a focus group approach [76]. Differently than with the panel, where the interaction with experts was individual and isolated, the experts were together within the focus group and provided their feedback to each other in real-time with verbalized exchange responses, rather than written ones, taking precedence over individual opinions of the participants [77]. The main goal was to reach a consensus more easily with moderation, stimulating constructive

discussions and capturing the experts' experiences and opinions [69]. The focus group was conducted in two steps to guarantee a consensus view, each lasting two hours, within a remote meeting using the Zoom platform. Both the panel and the focus group included an intermediary who acted as a moderator and was one of the authors of this paper, improving the likelihood of success of both methodological approaches [78].

2.3. Survey

The next methodological approach was based on a survey, following the guidelines provided by [79]. The survey was based on a questionnaire designed in five parts. Part 1 consists of a free and informed consent form, including the responsibility for the research, its objectives and main procedures, and an explanatory glossary of the main terms used. Part 2 relates to general information and data from the interviews. Part 3 focuses on the indicators for the barriers to sustainable I4.0 integration in the supply chains of MSMEs, while Part 4 focuses on the indicators for the enablers. Parts 3 and 4 apply a 5-point Likert scale (from strongly disagree up to strongly agree), aiming to validate the critical indicators obtained in the previous methodological research approaches. The barrier scale was adapted from [12,80–82]. In addition, the scale for enablers was considered from the perspective of [83–85]. Part 5 embraces the integration of I4.0 and TBL sustainability in supply chains of MSMEs from the PPT mechanisms and TBL dimensions perspectives, revealing their respective impact levels, and applies a 5-point Likert scale: "none or very mild", "mild", "moderate", "strong", and "very strong", adapted from [86,87].

Following [23], the questionnaire was organized based on the guidelines for designing Likert scale instruments from [88], whenever a scale was required, consisting of: (i) construct understanding; (ii) item development; (iii) the results space determination; (iv) classification model specification; and (v) feedback and pilot testing of the questionnaire. This last stage of feedback and testing was conducted with the seven experts of the panel to check the appropriateness of the language used, the clarity of the topics, and the time required to fulfill it completely.

Regarding the survey respondents, they were accessed in multiple ways: e-mail from the authors' bases, professional WhatsApp groups, and selection of thematic groups on LinkedIn focused on the themes of this research (e.g., Sustainable Procurement and Supply Chain, Industry 4.0 Ecosystem, The Digital Business and Industry 4.0, Fourth Industrial Revolution, Industry 4.0, Digitization, Industrial Robotics, Smart Manufacturing, Projects, Jobs and Careers). In all approaches, impacted people were encouraged to replicate the invitation to people who could meet the desired profile of the respondents. In the end, the survey counted 55 valid responses.

For the analysis of the survey, a multi-attribute decision-making method (MADM) [89,90] called the Additive Ratio Assessment (ARAS) method was used, which aims to deal with evaluation information that has different units of measurement [91]. The technique consists of five steps: (i) formalization of the decision-making matrix; (ii) data normalization; (iii) calculation of the normalized weighted matrix; (iv) optimality function; and (v) determination of the degree of usefulness and derivation of the final classification. The ARAS method is lauded for its simplicity and brevity, making it a user-friendly approach within the realm of MADM [92]. It can uniquely convert qualitative attributes into quantitative ones, thereby providing a more comprehensive analysis [93]. Furthermore, the ARAS method ensures the independence of attributes, a critical factor in decision-making processes [92]. Its diverse applications, such as in personnel recruitment and selection, demonstrate its versatility [92].

Moreover, the robustness and reliability of the ARAS method have been validated through the consistency of the final ranking of practices and the importance of the criteria with the findings of previous research [94]. Compared to other MADM methods, it is evident that ARAS holds several distinctive advantages. While all MADM methods aim to evaluate a finite set of alternatives based on multiple conflicting objectives [92], the ARAS method's ability to handle both qualitative and quantitative attributes sets it apart [93]. Additionally, the ARAS method's time efficiency is a significant advantage in real-time

implementation and dynamic environments [95]. The ARAS method is applied to support complex decision-making problems and choose the best alternative through the relative indicator (i.e., degree of utility), which can reflect the difference among the alternatives and the ideal solution and discard the influence of different measurement units [96]. Therefore, the ARAS method's unique features and advantages make it a valuable tool in the realm of MADM. In this study, this method was adapted through considering the results of prominence and cause/effect relationships obtained with the DEMATEL method in [23].

3. Integration of I4.0 and Sustainability in Supply Chains of MSMEs

This section first provides critical indicators for the barriers and enablers constructs and then the dominant barriers and enablers within the PPT mechanisms and TBL dimensions, organized within a first sketch for I4.0 and sustainability integration in the supply chains of MSMEs.

3.1. Critical Indicators for the Barriers and Enablers Constructs

This subsection addresses RQ-1 ("What are the critical indicators for the barriers and enablers of integrating I4.0 and sustainability in real-life settings of MSMEs' supply chains?"), revealing the results obtained with the scoping review, the panel of experts/focus group, and parts three and four of the survey. A first list of literature-based critical indicators emerged from the scoping review, which was refined and complemented towards an MSME perspective through a panel of experts and a focus group. Finally, the survey aimed to validate the critical indicators. The choice for a five-point Likert scale is adequate, and respondents' frequency of disagreement for indicators was low, ranging from 9.24% to 11.82%, which indicates support for this validation stage [97,98].

Table 1 offers the 16 indicators revealed for the barriers (two for each), and Table 2 provides the 16 indicators displayed for the enablers (two for each). Both tables are organized, offering in their first column the research code (with "B" for barriers and "E" for enables), their respective names in the second column, the item code in the third column, the name of the selected indicators in the fourth column displays, and the reference sources in the last column.

Table 1. Barriers to Sustainable I4.0 Integration in supply chains of MSMEs (Source: The Authors).

Code	Construct	Item	Indicator	Source
B1	Lack of technical expertise	B1.1	Lack of staff training of professionals	[99,100]
		B1.2	Lack of knowledge-sharing methodology and practices	[54,101]
B2	Cybersecurity issues	B2.1	Inadequate processes for monitoring and control	[23,70,102,103]
		B2.2	Weakness in cases of attacks and threats associated with the misuse of available information security technology	[35,104]
B3	Resistance to change, change management practices and adoption of innovation	B3.1	Lack of stimulus to innovation as a way of exploration and development of the company's capacity	[14,42]
		B3.2	Lack of effective management and/or governance and compliance system	[12,105]
B4	Lack of investment in R&D	B4.1	Lack of financial conditions and/or organizational structure	[54,106,107]
		B4.2	Lack of top management support	[108,109]

Table 1. *Cont.*

Code	Construct	Item	Indicator	Source
B5	Costs of upgrading and economic condition of OSCM	B5.1	Wrong procedures or low level of reuse and recovery of products	[110,111]
		B5.2	Low level of prioritization in the selection and use of products, services, and companies with sustainable practices, throughout the supply chain	[34,112,113]
B6	Lack of support from regulatory authority, weak legislation	B6.1	Low level of regulatory authority involvement and synergy with the company	[29,114–116]
		B6.2	Limited or obsolete legislation associated with recurrent innovations inherent to technological advancement	[117–120]
B7	Lack of top management commitment	B7.1	Lack of encouragement for shared and collaborative management	[121–123]
		B7.2	Lack of efficient communication, awareness campaigns	[124,125]
B8	Alternative resources and energy needs	B8.1	Lack of technical conditions or technological maturity for adequacy	[3,126,127]
		B8.2	Lack of funds for investments in appropriate technologies	[68,128,129]

Table 2. Enablers for sustainable I4.0 integration in supply chains of MSMEs (source: the authors).

Code	Construct	Item	Indicator	Source
E1	Top management commitment + Strategic alignment	E1.1	Existence of sustainable investments in information technology	[130,131]
		E1.2	Strategic and decision effectiveness	[132–134]
E2	Employee's empowerment + Knowledge sharing + Effective communication	E2.1	Existence of practices/training for the development of attitudes (towards the importance of I4.0 and sustainability)	[39,135,136]
		E2.2	Program for development of specific skills and specialists	[137–139]
E3	Internal innovation process	E3.1	Transformational leadership organizational innovation	[140–142]
		E3.2	Increase the adoption of digital manufacturing capabilities	[143,144]
E4	Data-centered solutions + Consistent data flow	E4.1	Consistent investments in centered and integrated information	[145,146]
		E4.2	Data flow that ensures usability	[147]
E5	Interdisciplinary and holistic integration + Life cycle thinking and circular processes	E5.1	Strategic integration of the operations	[3,7,148]
		E5.2	Use of dynamic monitoring systems	[149,150]
E6	Customer and supplier integration	E6.1	Implement effective communication in supply chain	[151–153]
		E6.2	Improve customer satisfaction	[154,155]

Table 2. *Cont.*

Code	Construct	Item	Indicator	Source
E7	Governmental and institutional pressures	E7.1	Authorization/inspection and regulation of operations	[156–158]
		E7.2	Management commitment and organizational structure to responsiveness of external pressures	[159–161]
E8	Valuation of R&D/research centers	E8.1	Actions/program for quality improvement and/or innovation in products/services in conjunction with R&D centers	[162,163]
		E8.2	Technological exchange responsiveness	[164,165]

3.2. Dominant Barriers and Enablers within the PPT Mechanisms and TBL Dimensions

This subsection addresses RQ-2 ("What are the dominant barriers and enablers within the PPT mechanisms and TBL dimensions regarding the integration of I4.0 and sustainability in the supply chains of MSMEs"). The Appendix A presents the results obtained from the survey. Tables A1 and A2 present findings for PPT mechanisms, respectively for barriers and enablers, and Tables A3 and A4 for TBL dimensions, also respectively for barriers and enablers. Tables 3 and 4 display the impact levels for integrating I4.0 and sustainability in the supply chains of MSMEs from the perspectives of PPT mechanisms and TBL dimensions, respectively, for barriers and enablers. Results were obtained using a variation of the ARAS method [91], in which, instead of considering the ranking of barriers and/or facilitators in each of the "axes" of the two dimensions, the barrier/facilitator was allocated to the "axis" in which it presented the highest score for that mechanism or dimension (highlighted in both tables). This dominance is highlighted in Tables 3 and 4 for all barriers and enablers (one for each PPT mechanism—in green and TBL dimension—in blue).

Building upon these research findings, Figure 2 presents a diagram with the dominant barriers (B) and enablers (E) within the PPT mechanisms and TBL dimensions, offering a first sketch for I4.0 and sustainability integration in the supply chains of MSMEs. It is labelled as a "first sketch", as it does not contemplate the causal and effects relationships or the influences among barriers and enablers, which are discussed later in Section 4.

Table 3. ARAS method for barriers.

	Economic	Environ.	Social	People	Process	Technology
B1	0.843130	0.815608	0.832527	0.821309	0.853053	0.813003
B2	0.878393	0.693337	0.728074	0.808457	0.802290	0.884597
B3	0.787279	0.775375	0.817745	0.900256	0.800364	0.729955
B4	0.835287	0.704704	0.681797	0.697936	0.742004	0.723651
B5	0.854444	0.78785	0.693159	0.671828	0.718692	0.735546
B6	0.708976	0.712017	0.688643	0.592859	0.641754	0.630998
B7	0.780220	0.769468	0.791294	0.753611	0.735954	0.630818
B8	0.754214	0.853793	0.747852	0.707832	0.74756	0.787845

Table 4. ARAS method for enablers.

	Economic	Environ.	Social	People	Process	Technology
E1	0.843871	0.802741	0.796163	0.892478	0.858459	0.782257
E2	0.771220	0.739911	0.777235	0.819092	0.780205	0.750948
E3	0.771936	0.787702	0.749858	0.721899	0.747779	0.686951
E4	0.803038	0.724309	0.697061	0.645855	0.746301	0.823665
E5	0.748944	0.802507	0.762297	0.728640	0.749786	0.709140
E6	0.869265	0.762289	0.723838	0.714353	0.772251	0.765769
E7	0.752181	0.809042	0.790227	0.661256	0.694421	0.635966
E8	0.808302	0.786677	0.711043	0.708560	0.699522	0.814398

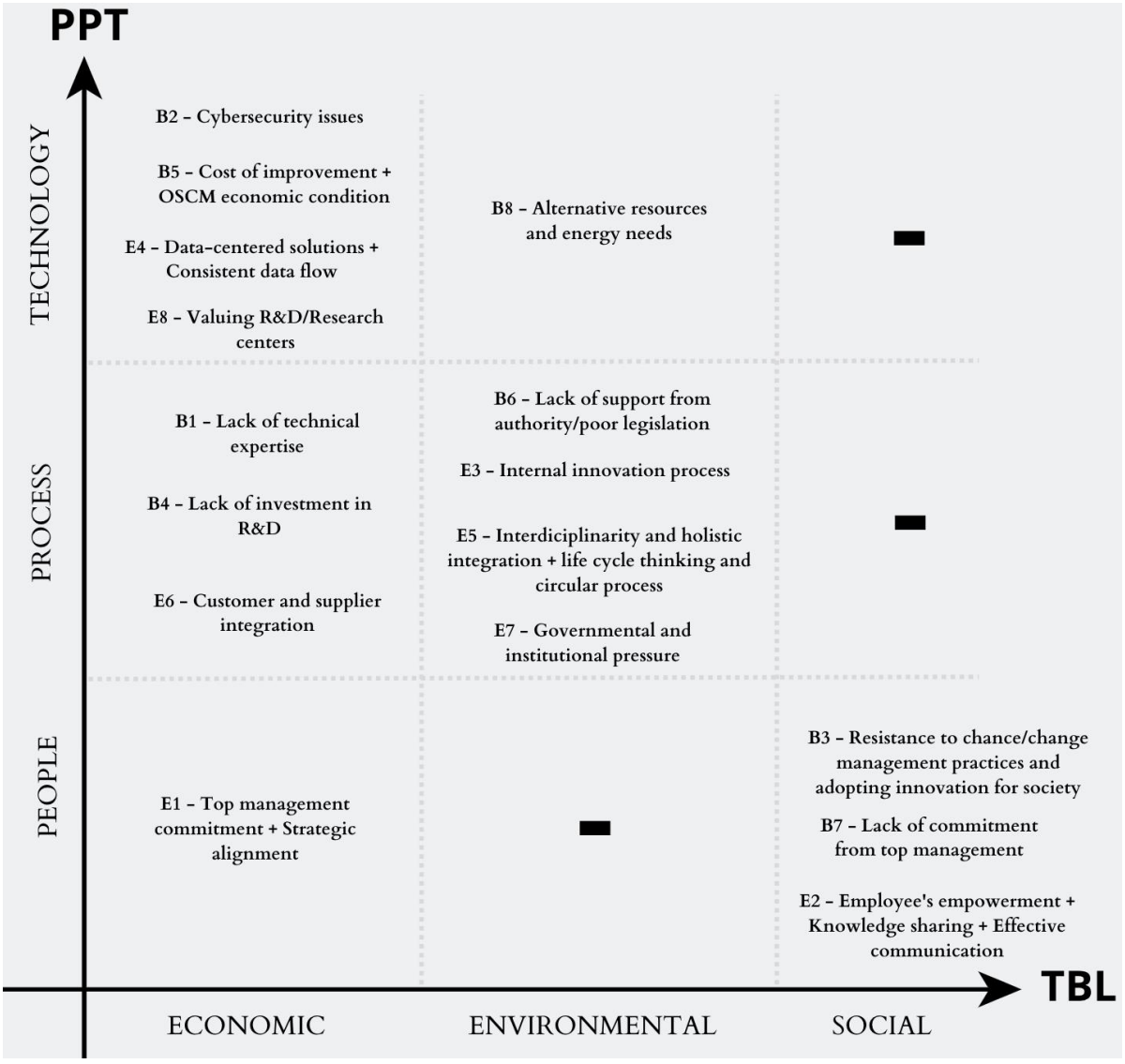

Figure 2. Sketch for I4.0 and sustainability integration in supply chains of MSMEs (source: the authors).

The sketch analysis offered in Figure 2 can be understood through an interplay perspective and the mechanisms/dimensions' analysis. Next, examples of such analyses are provided. The intention is not to be exhaustive but to show how the sketch can aid MSMEs towards I4.0 and sustainability integration in their supply chains.

Through the interplay analysis, one can notice a greater number of dominant barriers/enablers present at the interplays of the environmental dimension/process mechanism and the economic dimension/technology mechanism (four for each), and then the interplays of the social dimension/people mechanism and the economic dimension/process mechanism (three for each), which requires herein greater attention from MSMEs. For instance, the first interplay of the environmental dimension/process mechanism embraces three enablers (E3, E5, and E7), which indicates it can be an arena for MSMEs to leverage the integration of I4.0 and sustainability in their supply chains through the indicators of "transformational leadership organizational innovation" [140–142], "increase the adoption of digital manufacturing capabilities" [143,144], "strategic integration of the operations" [3,7,148], "use of dynamic monitoring systems" [149,150], "authorization/inspection and regulation of operations" [156–158], "management commitment and organizational structure to the responsiveness of external pressures" [159–161], "low level of regulatory authority involvement and synergy with the company" [29,114,115], and "limited or obsolete legislation associated with recurrent innovations inherent to technological advancement" [117–120].

Through individual analysis, analyzing the barriers, the economic dimension of the TBL is the most challenging one, as it offers four different barriers, two associated with technology (B2 and B5) and another two with process (B1 and B4). MSMEs need to face them towards leveraging the economic dimension of "inadequate processes for monitoring and control" [6,23,70,102], "weakness in cases of attacks and threats associated with the misuse of available information security technology" [35,104], "wrong procedures or low level of reuse and recovery of products" [110,111], "low level of prioritization in the selection and use of products, services, and companies with sustainable practices, throughout the supply chain" [34,112,113], "lack of staff training of professionals" [99,100], "lack of knowledge sharing methodology and practices" [54,101], "lack of financial conditions and organizational structure" [54,106,107], and "lack of top management support" [108,109]. From the mechanism perspective, the process is associated with four enablers (E3, E5, E6, and E7), offering a great perspective to leverage I4.0 and sustainability integration in the supply chains of MSMEs.

It is observed that the social dimension of TBL has fewer dominant barriers and enablers, which may be a result of its newness influencing data collection, as maturity in this dimension among experts may still be incipient. To investigate this observation, future research should be carried out. The fact that this dimension only has interaction with people could also point in this direction, as people mechanisms could be easier to associate with the social dimension than process and technology mechanisms, which are therefore dominant. It is important to remember that it is possible to make additional analyses beyond the aspect of dominance, but also that they are not in the scope of the present study.

From the lens of the I5.0 paradigm, which aims to seamlessly integrate human and machine intelligence sustainably, each barrier group could be confronted through a set of I5.0 principles [59] that serves as a solution for S-I4.0 integration. For instance, the barriers associated with technical expertise (B1) and cybersecurity issues (B2) are, respectively, addressed through the principles of collaboration/knowledge sharing, training [54,99–101], monitoring/control coordination, and information security technology [23,35,70,102–104]. These principles enhance the capabilities of I5.0 systems, ensuring effective monitoring and control of, and response to, threats [59]. Similarly, barriers related to resistance to change, change management practices, and adoption of innovation (B3) are countered by innovative technological decisions, development of the company's capacity [12,34,42,119], effective management, and governance/compliance systems [12,105]. This fosters a human-centric approach, promoting ethical utilization of technology and facilitating a smoother transition to innovative practices.

The lack of investment in research and development (B4) is mitigated through top management support [108,109] and improvement of organizational structure. This allows for dynamic adaptation of manufacturing and supply chain systems, overcoming finan-

cial challenges and organizational limitations [54,106,107]. Economic challenges, such as upgrading costs and economic conditions (B5), are effectively handled by principles emphasizing sustainability [110,111] and viability in the selection and use of products and services [34,112,113]. This entails a shift toward a "new TBL", prioritizing resilient value conception, human welfare, and sustainable society. Societal-level considerations (B6), including a lack of support from regulatory authorities, find resolution through principles advocating for authorization, inspection, and ethical technological advancement. This ensures a supportive regulatory environment aligned with I5.0 objectives [29,114–116].

Furthermore, the absence of top management commitment (B7) is addressed by collaborative decision-making [121–123], efficient communication, and awareness campaign principles [124,125]. These promote human-centric ecosystems, encouraging shared management and commitment from top-level executives. Finally, alternative resources and energy needs (B8) are met through technical conditions for adequacy [3,126,127], and the need for funds via investments in appropriate technologies [68,128,129]. I4.0 technologies like the Internet of Things (IoT) play a pivotal role in addressing energy needs and enhancing overall sustainability. Considering the list of enablers, an enabler that could align closely with addressing the absence of top management commitment (B7) is E7—Governmental and institutional pressures. Specifically, principles related to E7.2—Management commitment and organizational structure to the responsiveness of external pressures [159,160] can play an important role in fostering the necessary commitment and engagement from top-level executives, thus facilitating a more effective transition to I5.0 and overcoming barriers to S-I4.0 integration.

4. S-I4.0 Framework Applied to Supply Chains of MSEs and MEs

This section addresses RQ-3 ("What are the causal and effect relationships, as well as the influence among barriers and enablers, regarding the integration of I4.0 and sustainability in the supply chains of MSMEs from a PPT and TBL perspective?") and complements the research findings presented previously in Section 3, leading to the proposed framework for I4.0 and sustainability integration (S-I4.0) in the supply chains of MSMEs. Barriers and enablers in the causal and effect groups for MSMEs are analyzed in [23], who conclude that there are variations for both when it comes to the size of the company (MSEs or MEs), in addition to presenting different influences between these constructs that also depend on the size of the company. Therefore, the framework is adapted for MSEs and MEs.

Figures 3 and 4 present the S-I4.0 framework applied to supply chains for MSEs and MEs, segregating barriers (left side) from enablers (right side) to ease visualization. There is a three-tone legend in green colors to facilitate the origin and destination of influences through the indicated arrows. For both barriers and enablers, Figures 3 and 4 show a higher frequency in the economic dimension of the TBL, always with four of the eight barriers or enablers, that is, 50% of the frequency, with one barrier or enabler classified as causal. Regarding barriers for MSEs and MEs, the frequency is two for the environmental and social dimensions of the TBL. Concerning enablers for MSEs and MEs, the frequency is three for the environmental dimension and one for the social dimension of the TBL. Regarding the axis of PPT mechanisms for barriers, there is a greater frequency balance for both MSEs and MEs, where the frequency is three for the technology mechanism, three for the process, and two for people. Still for PPT, but now for enablers, there is a greater frequency in the process mechanism, with five enablers, than in people, with two, and with one frequency in the technology mechanism. It is observed in the environmental mechanism in the PPT axis that there are no influencing barriers or enablers; when they appear in the relationship, they are always with an influenced variable.

B1 and B7 can be highlighted as causal barriers for both MSEs and MEs, with MEs having more influence relationships for both. It is important to emphasize that B7 influences B1 in both cases. B5 also draws attention to the greater relevance of costs of improvement & OSCM economic condition in MSEs. Concerning enablers, E1 plays a leading role in MSEs and MEs, with E1 influencing E2 in both cases, with E2 being a causal enabler in

MSEs and an effect enabler in MEs. E4 appears as an influencing barrier in MSEs, being replaced by E8 in MEs. When delving deeper into the analysis of Figures 3 and 4 regarding the similarities or complementarities between the most impactful barriers and enablers, it is plausible to recommend that both managers of MSEs and MEs focus primary care on B7 and E1, concentrating attention on eliminating the lack of top management commitment, in addition to the potential related to the organization's strategic alignment. It is also noted that for MEs, E8 assumes relevance for the organization, and it is recommended to establish a budget and specific processes for sustainable results related to research and development.

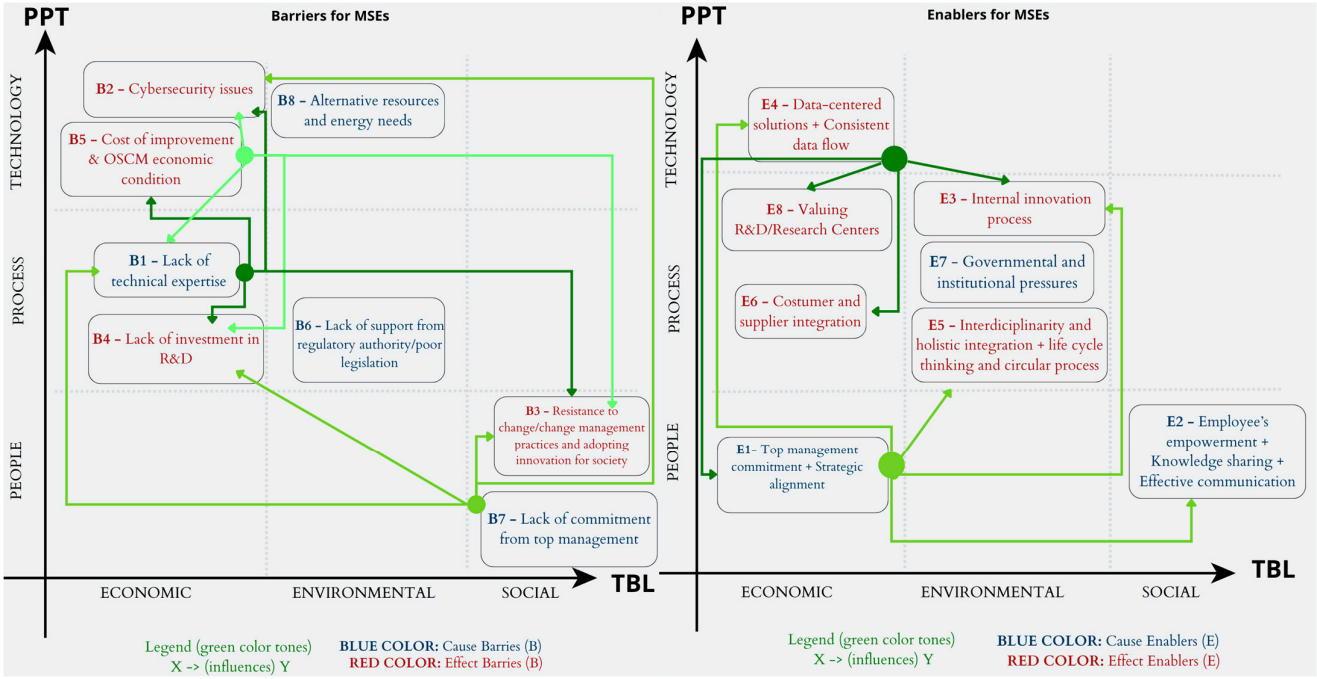

Figure 3. S-I4.0 framework applied to supply chains of MSEs (source: the authors).

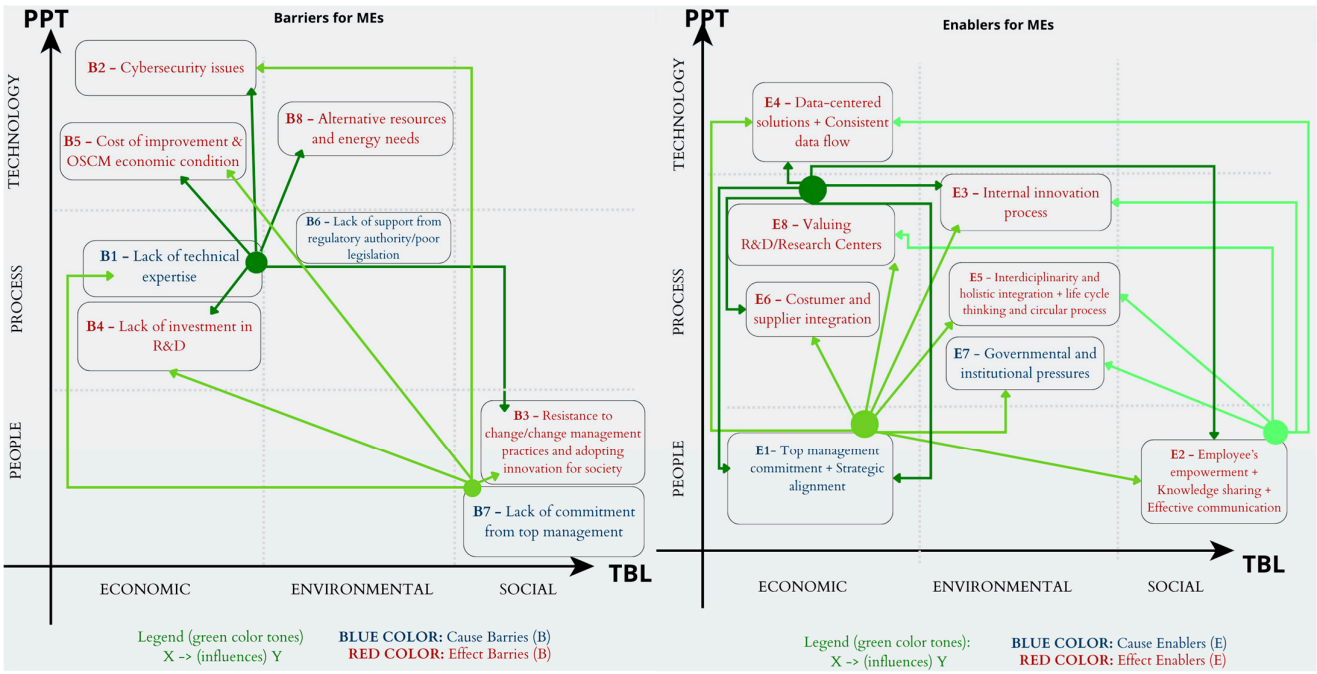

Figure 4. S-I4.0 framework applied to supply chains of MEs (source: the authors).

The frameworks in Figures 3 and 4 present additional information relevant to managers of MSEs and MEs, given that: (i) B7 (social—TBL and people—PPT) is a fundamental barrier as it influences B1; (ii) E1 (economic—TBL and people—PPT) is a fundamental enabler as it influences E2; (iii) for MSEs, B5 (economic -TBL and technology—PPT) highlights the criticality of barriers associated with the cost of change for smaller companies, and E4 (economic—TBL and Technology—PPT) highlights the importance of enablers that allow greater flexibility and agility; and (iv) for MEs, E8 (economic—TBL and process—PPT) highlights that partnerships with research and development organizations are important.

Additionally, Figures 3 and 4 present additional findings on the influences between barriers and enablers. Looking at barriers, it is noted that the number of main influencers is three for MSEs and decreases to two for MEs. The B5 barrier no longer influences the context of MEs. The opposite happens for enablers; there are two enablers for MSEs, and this increases to three for MEs. The E2 enabler starts to influence in the context of MEs.

In Figure 3 (Barriers and enablers for MSEs—TBL and PPT axis), cause (C) barriers are B1, B6, B7, and B8. Effect (E) barriers are B2, B3, B4, and B5. B1 (C) influences B2 (E)/B3 (E)/B4 (E)/B5 (E). B5 (E) influences B1 (C)/B2 (E)/B3 (E)/B4 (E). B7 (C) influences B1 (C)/B2 (E)/B3 (E)/B4 (E). Cause enablers are E1, E2, and E7. Effect barriers are E3, E4, E5, E6, and B8. E1 (C) influences E2 (C)/E3 (E)/E4 (E)/E5 (E). E4 (E) influences E1 (C)/E3 (E)/B6 (E)/E8 (E).

In Figure 4 (Barriers and enablers for MEs—TBL and PPT axis), the cause barriers are B1, B6, and B7. Effect barriers are B2, B3, B4, B5, and B8. B1 (C) influences B2 (E)/B3 (E)/B4 (E)/B5 (E)/B8 (E). B7 (C) influences B1 (C)/B2 (E)/B3 (E)/B4 (E)/B5 (E). Cause enablers are E1 and E7. Effect barriers are E2, E3, E4, E5, E6, and B8. E1 (C) influences E2 (C)/E3 (E)/E4 (E)/E5 (E). E2 (E) influences E3 (E)/E4 (E)/E5 (E)/E7 (C)/E8 (E). E8 (E) influences E1 (C)/E2 (E)/E3 (E)/E4 (E)/E6 (E).

Examining the identified barriers and enablers through the lens of I5.0 reveals nuanced cause-and-effect relationships, particularly when considering contingent factors such as company size and the unique context of a developing country (i.e., Brazilian companies). These intricacies shed light on the differentiated impacts and challenges MSEs and MEs face in adopting I5.0 principles. In the Brazilian context, the lack of technical expertise (B1) holds distinct implications for MSEs and MEs. While both groups face the challenge of insufficient staff training (B1.1) [99,100] and knowledge-sharing practices (B1.2) [54,101], the influence of top management commitment (B7) as a causal barrier is more pronounced for MEs. The size-related dynamics suggest that larger enterprises may encounter additional complexities in fostering a commitment to shared and collaborative management (B7.1) [122,123,166] and efficient communication (B7.2) [124,125], emphasizing the need for tailored strategies based on company size within the Brazilian landscape. Similarly, the barriers related to costs of upgrading and economic conditions (B5) exhibit a greater relevance for MSEs in the Brazilian context. The economic challenges smaller companies face highlight the criticality of barriers associated with the cost of change, underscoring the need for targeted interventions to alleviate financial constraints and facilitate the integration of sustainable practices throughout the supply chain [34,112,167].

Enablers such as (E1) and (E2) play a leading role in both MSEs and MEs. However, the causal relationship between these enablers is more pronounced for MSEs, where top management commitment becomes a crucial factor influencing the development of specific skills and specialists (E2.2) [137–139]. The adaptability and agility inherent in I5.0 principles become particularly relevant for MSEs in navigating the challenges posed by limited resources and financial conditions.

Moreover, in a developing country like this, where regulatory and legislative frameworks may be evolving, (B6) can present unique challenges. The limited involvement and synergy between regulatory authorities and companies (B6.1) [29,114,115] may disproportionately affect MSEs, highlighting the need for a more supportive regulatory environment to facilitate technological advancement.

5. Conclusions

This paper adopts a mixed-method approach, combining literature-based insights with empirical insights, to address a significant gap in research practice related to integrating I4.0 and sustainability in the unresearched supply chains of MSMEs. The main contributions in this regard are: First, it reveals 32 critical indicators for barriers and enablers (two for each), helping to understand these constructs for integrating I4.0 and sustainability in MSME supply chains, addressing RQ-1. Next, the dominant barriers and enablers within the PPT mechanisms and TBL dimensions to this integration are identified, addressing RQ-2, and their causal and effect relationships and their respective influences are revealed, addressing RQ-3. Finally, the research results are synthesized in a novel S-I4.0 framework, aimed towards achieving the paper's main goal.

Research findings provide practical implications and contributions for managers of MSEs and MEs concerning the acceleration of the S-I4.0 adoption process in their settings. The S-I4.0 framework is applied, focusing on the supply chains of MSEs and MEs. The strength of the economic dimension is evident in the TBL axis for both barriers and enablers for MSEs and MEs. In the PPT axis for barriers, there is a balance in frequency distribution, while for enablers frequency is predominant in the process mechanism.

Another important contribution regards the need to treat MSEs and MEs differently. Although they can share the same barriers and enablers, the way these constructs are handled in terms of causal and effect relationships and their influences vary according to firm size (MSEs or MEs). On the one hand, MSE managers, for instance, should focus on barriers as they influence more than in MEs. On the other hand, ME managers must devote more attention to enablers in the search for greater impact on business. As presented in Section 4 of this study, barrier B5 (Cost of improvement & economic condition of OCSM) is a barrier of greater relevance and influence in the context of MSEs than in the context of MEs. Two other barriers of relevance and influence in both contexts are B1 (Lack of technical expertise) and B7 (Lack of commitment from top management). Therefore, in terms of dealing with barriers, it makes sense to concentrate efforts on involving top management and strengthening technical teams with specialized professionals. When it comes to enablers, the situation of relevance and influence is different. Enabler E1 (Top management commitment + Strategic alignment) should receive attention in both MSE and ME contexts. In the case of MSEs, the E4 enabler (Data-centered solutions + Consistent data flow) also stands out. Regarding MEs, two other enablers, E2 (Employee's empowerment + Knowledge sharing + Effective communication) and E8 (Valuing R&D/Research Centers), also play a central role in terms of relevance and influence. In terms of enablers, the complexity increases, making the biggest challenge for managers of MSEs or MEs understanding what situation their company is in and, based on this analysis, carrying out actions that enhance the appropriate enablers. The natural path is to migrate from being an MSE to an ME within the company's growth trajectory, but the opposite path may occur, wherein appropriate actions must also be adopted, observing this direction of reducing the company's size. A company's sense of contraction can be even more challenging as these are measures that represent cuts in people, processes, technology, tools, licenses, and contracts, among other components.

One direct way to begin in the practice of MSEs and MEs can be with the people mechanism in the PPT axis with actions that enable the direct commitment of shareholders. In the TBL axis, the economic and social dimensions require more attention and investment due to both the influence and the transformative impact caused. Furthermore, in the PPT axis, the process mechanism is how transformations occur in practice, and it is extremely important due to the frequency of barriers and enablers present. Additionally, the technology mechanism in the PPT axis and the environmental dimension in the TBL axis are relevant in this journey and should receive suitable attention according to the reality of the MSEs and MEs involved. This information is another contribution for practitioners when dealing with barriers and enablers, within MSE and ME organizations, towards I4.0 and sustainability integration in their supply chains.

Considering I5.0 within developing countries' contexts, the importance of technology-driven innovation is magnified. The collaborative adoption of I4.0 technologies becomes a key determinant of success. MSEs, with their resource constraints, may find innovative solutions to bridge technological gaps, emphasizing the significance of socio-centric technological decisions and the use of technology to advance human values and needs. Therefore, I5.0's applicability in the context of Brazilian MSEs and MEs highlights the necessity for a nuanced comprehension of company size and the unique challenges posed by a developing country's landscape. Tailoring strategies to address contingent factors is crucial for unlocking the transformative potential of I5.0 and fostering sustainable and resilient operations in a diverse and dynamic industrial ecosystem.

This research has limitations and consequently presents several opportunities for continuity. Future research could support MSMEs' journey towards Industry 4.0 and sustainability integration in their supply chains. Although this research has embraced empirical insights through different approaches, additional empirical findings could be obtained by applying the framework in a case or multiple-case study. Moreover, one can explore deeper the barriers and enablers, going beyond the issue of dominance, by prioritizing the impact levels for the integration of I4.0 and sustainability in the supply chains of MSMEs from the PPT mechanisms and TBL dimensions perspectives. Regarding indicators, there is space to check their applicability, to prioritize analysis, or even to rank them depending on a company's evolutionary stage, for instance. The metrological component is also an opportunity to measure barriers, enablers, and indicators, from identifying the sources to extracting measurements/values to their presentation and use by MSME managers. Finally, sustainability has become more important in the scenario of the implementation of I4.0 in the supply chains of MSMEs. However, this can be even more impactful when the visions projected for I5.0 or Society 5.0 are considered [48,50], as well as the growing importance given by public and private markets to the UN's sustainable development goals [53], or by the unique situation with exceptional resources in periods of global crises, framed by the hostile scenario of the pandemic and negative post-pandemic projections [56]. Therefore, more research should be conducted towards deepening the understanding of indicators of the barriers and enablers targeted in this research to support MSMEs and their supply chains in achieving a new level of operation that can enable these new visions and challenges.

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Appendix A

Table A1. Barriers' impact levels (PPT).

Integration I4.0 to PPT	None or Very Mild	Mild	Moderate	Strong	Very Strong	Total Sample
B1 People	1	5	7	20	22	55
B1 Process	0	4	6	30	15	55
B1 Tech	1	2	8	21	23	55
B2 People	0	4	12	19	20	55
B2 Process	2	1	8	30	14	55
B2 Tech	0	4	5	19	27	55
B3 People	0	2	4	23	26	55
B3 Process	0	3	11	31	10	55
B3 Tech	1	2	23	17	12	55
B4 People	2	6	10	25	12	55
B4 Process	1	5	13	24	12	55
B4 Tech	3	4	13	19	16	55
B5 People	2	6	14	22	11	55
B5 Process	1	6	14	24	10	55
B5 Tech	1	5	12	21	16	55
B6 People	5	6	15	20	9	55
B6 Process	4	3	16	23	9	55
B6 Tech	3	8	14	20	10	55
B7 People	3	3	5	25	19	55
B7 Process	2	3	10	29	11	55
B7 Tech	4	5	15	19	12	55
B8 People	2	4	19	21	9	55
B8 Process	1	5	17	23	9	55
B8 Tech	0	3	13	23	16	55

Table A2. Enablers' impact levels (PPT).

Integration I4.0 to PPT	None or Very Mild	Mild	Moderate	Strong	Very Strong	Total Sample
E1 People	0	4	8	23	20	55
E1 Process	1	2	8	25	19	55
E1 Tech	1	1	16	25	12	55
E2 People	2	1	3	22	27	55
E2 Process	2	1	4	32	16	55
E2 Tech	2	3	14	22	14	55
E3 People	3	2	10	22	18	55
E3 Process	2	3	6	24	20	55
E3 Tech	2	4	17	20	12	55
E4 People	3	5	18	16	13	55
E4 Process	1	4	15	20	15	55
E4 Tech	2	2	8	16	27	55

Table A2. *Cont.*

Integration I4.0 to PPT	None or Very Mild	Mild	Moderate	Strong	Very Strong	Total Sample
E5 People	2	3	10	20	20	55
E5 Process	3	1	11	20	20	55
E5 Tech	2	1	22	16	14	55
E6 People	1	4	15	17	18	55
E6 Process	1	3	9	22	20	55
E6 Tech	1	3	12	23	16	55
E7 People	1	9	17	15	13	55
E7 Process	2	7	14	16	16	55
E7 Tech	4	7	19	17	8	55
E8 People	2	2	19	17	15	55
E8 Process	2	3	19	18	13	55
E8 Tech	1	4	8	27	15	55

Table A3. Barriers' impact levels (TBL).

Integration I4.0 to TBL	None or Very Mild	Mild	Moderate	Strong	Very Strong	Total Sample
B1 Eco	0	3	7	25	20	55
B1 Env	0	5	13	27	10	55
B1 Soc	0	4	16	23	12	55
B2 Eco	0	4	8	16	27	55
B2 Env	3	5	22	16	9	55
B2 Soc	1	5	21	19	9	55
B3 Eco	0	3	14	24	14	55
B3 Env	1	2	18	24	10	55
B3 Soc	0	6	12	23	14	55
B4 Eco	0	6	10	16	23	55
B4 Env	3	5	15	23	9	55
B4 Soc	1	8	16	19	11	55
B5 Eco	0	4	6	25	20	55
B5 Env	0	3	19	22	11	55
B5 Soc	2	5	22	18	8	55
B6 Eco	2	3	22	14	14	55
B6 Env	1	7	18	16	13	55
B6 Soc	3	8	15	16	13	55
B7 Eco	0	5	12	22	16	55
B7 Env	1	4	18	22	10	55
B7 Soc	0	6	13	24	12	55
B8 Eco	0	3	20	20	12	55
B8 Env	0	2	18	17	18	55
B8 Soc	0	8	19	21	7	55

Table A4. Enablers' impact levels (TBL).

Integration I4.0 to TBL	None or Very Mild	Mild	Moderate	Strong	Very Strong	Total Sample
E1 Eco	0	4	12	22	17	55
E1 Env	1	6	13	22	13	55
E1 Soc	2	3	14	28	8	55
E2 Eco	0	2	21	22	10	55
E2 Env	1	6	19	20	9	55
E2 Soc	0	5	18	23	9	55
E3 Eco	1	3	16	20	15	55
E3 Env	0	5	16	24	10	55
E3 Soc	1	7	16	22	9	55
E4 Eco	1	3	12	24	15	55
E4 Env	2	5	20	16	12	55
E4 Soc	2	7	20	15	11	55
E5 Eco	1	5	16	21	12	55
E5 Env	1	7	12	17	18	55
E5 Soc	2	6	14	20	13	55
E6 Eco	0	4	8	20	23	55
E6 Env	0	7	19	17	12	55
E6 Soc	1	9	18	20	7	55
E7 Eco	2	6	14	17	16	55
E7 Env	2	6	14	20	13	55
E7 Soc	4	5	17	14	15	55
E8 Eco	0	5	14	20	16	55
E8 Env	0	8	13	22	12	55
E8 Soc	2	6	23	18	6	55

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