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Integration of the Food Supply Chain as a Driver of Sustainability: A Conceptual Framework

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Abstract: This paper presents a conceptual framework aimed at exploring the connections between integration within the food supply chain and the three pillars of sustainability: economic, environmental, and social. The analysis combines theoretical insights with empirical research, specifically focusing on the economic aspect of sustainability, measured through efficiency. The study emphasizes the critical role of integrating participants across the food supply chain to achieve sustainability goals. It discusses methodologies for assessing integration levels within the chain, providing a theoretical and analytical basis for modeling integration and efficiency within the supply chain. To empirically validate these relationships, an extended stochastic frontier analysis (SFA) method was applied to selected sectors within the food processing industry. The results demonstrate that enhancing integration with suppliers and buyers can significantly improve efficiency within the food chain. In conclusion, through deductive reasoning, this study asserts that integration plays a pivotal role in advancing economic sustainability objectives within the food sector. This framework contributes to a deeper understanding of how integration influences sustainability outcomes, offering valuable insights for stakeholders aiming to enhance sustainability in food systems.

Keywords: food supply chain; integration; sustainability; stochastic frontier analysis

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1. Introduction

Supply chains are vital for meeting the dynamic demands of consumers in competitive markets. Their management is complex due to the involvement of numerous stakeholders, processes, and uncertainties [1]. Successful management requires aligning strategies with business objectives, optimizing performance, and utilizing network resources, which is especially relevant for food supply chains. Food supply chains are critical for global food production and distribution, with inherent challenges such as ensuring traceability, safety, sustainability, and quality under stringent deadlines [2–4].

Sustainability challenges in food supply chains are multifaceted, encompassing economic, environmental, and societal dimensions. The complexity of modern food systems necessitates a shift towards more sustainable practices, considering factors like food loss and waste reduction [5], the integration of digital technologies for traceability and safety [6], and the emergence of short food supply chains as a more eco-friendly alternative [7]. Manzini and Accorsi [8] emphasize the importance of addressing future challenges in both public and private research, specifically focusing on the role of integration. They advocate for a new and effective approach to food supply chain (FSC) assessment that simultaneously manages quality, safety, sustainability, and efficiency. These challenges are exacerbated by issues such as declining land sizes, population growth, and consumer demands, highlighting the need for transparent and strategic agribusiness supply chains that align with social, environmental, and economic goals [9]. Addressing these challenges requires a holistic approach that considers the entire food supply chain, from production to consumption, while embracing innovative solutions and sustainable practices to ensure long-term viability and resilience in the face of global challenges.

Supply chain integration (SCI) plays a crucial role in addressing sustainability issues within companies by enhancing environmental performance and financial outcomes. According to Flynn et al. [10], supply chain integration involves the strategic collaboration between manufacturing firms and their supply chain partners to effectively utilize both internal and external resources and capabilities throughout the entire supply chain. Research highlights that SCI can lead to achieving supply chain sustainability (SCS) by effectively managing internal and external contextual factors influencing this relationship [11]. Supply chain sustainability management is the management of material, information, capital flows, and cooperation among companies along the supply chain, while taking into account goals (which are derived from customer and stakeholder requirements) from all three dimensions of sustainable development, i.e., economic, environmental, and social [12]. Research has shown that SCI positively impacts overall sustainable supply chain performance (OSSCP) by driving ethically higher supply chain levels and improving efficiency in operations [13]. Furthermore, the development of environmental capabilities within firms, along with supply chain integration, enhances environmental and financial performance, highlighting the importance of environmental capability development as a strategic objective for promoting environmental sustainability along the supply chain [14]. Additionally, SCI contributes to economic, environmental, and social sustainability by improving production process reliability, reducing the carbon footprint, and enhancing social aspects related to increases in human labor [15]. The integration of digital technologies like cloud computing, artificial intelligence, and big data analysis improves the efficiency and responsiveness of the supply chain, leading to sustainability in digitally integrated supply chains [16]. Additionally, the development of supply chain quality integration and green supply chain practices contributes to driving sustainability performance, emphasizing the importance of internal environmental management in achieving sustainability goals [17]. Furthermore, the implementation of blockchain-driven supply chains is highlighted as a strategic approach to attaining supply chain sustainability by improving traceability and visibility and reducing waste in production and distribution [18]. Studies emphasize that the involvement of supplier companies in sustainability transitions, particularly in allocating resources to address issues like animal welfare, is influenced by supply chain factors, institutional variables, and internal innovativeness, showcasing the importance of collaboration across the supply chain for sustainability initiatives [19].

Integrating companies in the supply chain is essential for effectively addressing sustainability challenges. This is particularly important in the context of food supply chains, which are characterized by a significant degree of complexity and a large number of actors. Addressing sustainability within food supply chains requires targeted strategies that account for the intricate interactions and dependencies among various stakeholders. Integrating food supply chains can lead to sustainability by addressing various challenges and opportunities present in the global food supply chain (FSC) [20]. Efforts to reduce food loss and waste (FLW) through improved coordination among all actors within the supply chain can enhance sustainability by minimizing economic losses and reducing environmental impact [21]. Additionally, the introduction of innovative technologies like blockchain networks can revolutionize governance and transparency in food systems, contributing to sustainable development goals and ensuring traceability and accountability throughout the supply chain [20]. Overall, integrating food supply chains with a focus on collaboration, technology adoption, and efficient logistics can significantly contribute to achieving sustainability goals in the food industry [22].

This article underscores the economic pillar of sustainability, emphasizing the role of integration in achieving and enhancing sustainability goals. The central research question explores how integration can bolster efficiency and how integrating processes within the food supply chain can drive sustainability. This study employs a robust methodological framework to analyze the impact of supply chain integration on efficiency within the food sector. Data were collected from firms in the dairy, meat, and fruit and vegetable sectors. The analysis specifically examines the efficiency of enterprises within the supply chain, incorporating the measurement of integration into the stochastic frontier analysis (SFA) function. This measurement encompasses integration with both suppliers and customers. To quantify integration levels, this study developed the supply chain integration degree measure (SCIDM) and integrated this measure into the SFA model to evaluate its effect on efficiency. Maximum likelihood estimation techniques and likelihood ratio tests were used to validate the models across multiple periods, providing comprehensive insights into the relationship between supply chain integration and efficiency. The methods employed in this study are detailed in Section 3, in which the approaches and techniques used for analysis are thoroughly described.

By adopting a comprehensive approach that combines theoretical foundations with empirical validation, this study aims to elucidate the complex relationship between supply chain integration and efficiency, particularly in the context of economic sustainability within the food sector. While the existing literature offers initial insights into the relationship between supply chain integration and company efficiency, empirical studies often neglect its impact on achieving sustainability goals. This article addresses this gap by integrating theoretical perspectives with empirical evidence to rigorously quantify the effects of supply chain integration on operational efficiency and its subsequent contribution to sustainability.

2. Theoretical Background

2.1. Enhancing Sustainability across Economic, Environmental, and Social Dimensions

Achieving success in economic, environmental, and social spheres is essential for companies facing the current demands regarding environmental and social responsibility. Sustainable development encompasses a wide range of issues related to consumption and waste, including food and agriculture production and usage; natural resource utilization; population growth; quality of life; biodiversity; waste generation; and pollution of air, land, and water, as well as recycling and reuse initiatives. Within the framework of sustainability, these identified challenges can be effectively addressed through the integration of economic entities. In this context, various forms of integration have the potential to play a crucial role in preserving and enhancing economic, environmental, and social resources.

Various forms of integration provide a broad range of intermediate solutions that bridge market mechanisms and hierarchical structures, addressing the weaknesses inherent in market failure. Market failure, characterized by transaction costs, uncertainty, economies of scale, opportunism, trust issues, externalities, asset specificity, social inequity, and information asymmetry, plays a significant role in shaping various forms of integration. Organizational strategies like supply chain integration are seen as avenues to harness or address these weaknesses within the market. By mitigating functional shortcomings through integrated supply chains, companies can contribute to the three key sustainability dimensions. The relationships within each pillar of sustainability indicate the following connections, as shown in Table 1.

In terms of economic sustainability, supply chain integration provides several critical benefits by enhancing efficiency and reducing transaction costs. By shortening supply chains and fostering closer coordination between participants, integration significantly diminishes the resources consumed throughout production and operational processes. This streamlined approach reduces transaction costs and eliminates redundancies, which contributes to creating added value across the supply chain. Moreover, the reduction in uncertainty and opportunism that often plagues supply chain relationships leads to a more stable and predictable environment. Improved communication and coordination minimize the need for extensive control and risk assessment measures, thereby further reducing resource expenditure. As a result, supply chain integration enhances overall efficiency and profitability. Furthermore, the establishment of long-term partnerships and investments as a result of integration reduces capital specificity and promotes economies of scale, reinforcing the economic sustainability of the supply chain.

Table 1. Enhancement of economic, environmental, and social aspects of sustainability through supply chain integration.

Limitation of Market Weaknesses through Integration	Pillar of Sustainability
Reduction of transaction costs	Economic sustainability
Mitigation of uncertainty, opportunism, and trust deficits	Economic sustainability
Reduction of information asymmetry	Environmental sustainability
Reduction of external effects	Environmental sustainability
Reduction of social inequality	Social sustainability
Information flow	Social sustainability

Source: own elaboration.

From an environmental perspective, supply chain integration plays a crucial role in mitigating the effects of information asymmetry regarding products and processes. Bridging these informational gaps enables the more informed and conscientious management of natural resources, such as water, land, and air. Integration helps in reducing external environmental impacts, such those caused by emissions from wastewater discharge, soil contamination from fertilizers, and air pollutants. This improved management promotes better resource utilization and minimizes waste, which collectively enhances the environmental performance of the supply chain. By optimizing processes and resource use, integration supports the overall goal of reducing the supply chain's environmental footprint, contributing to a more sustainable operation.

Regarding social sustainability, supply chain integration fosters trust and equity among stakeholders by promoting fair labor practices and equitable resource distribution. Enhanced transparency and the flow of information about products, processes, and resource allocation help in addressing social inequalities and improving labor conditions. The integration of supply chains facilitates better communication and collaboration between stakeholders, leading to increased community welfare and social stability. By ensuring that all participants benefit equitably from the supply chain operations and by promoting fair practices, integration contributes significantly to the broader goal of social sustainability.

2.2. Efficiency and Integration

The concept of efficiency in economic entities is complex and multifaceted. Various definitions, measurement methods, and expressions exist, each offering a different perspective. While many terms are used interchangeably to describe efficiency, they are not always equivalent. The understanding of efficiency is linked to the structure of the production function, reflecting variations in the productivity of production factors and their remuneration (see Section 3.3). Efficiency focuses on the optimal allocation of production inputs to achieve maximum technical effectiveness. Therefore, in this paper, the production function serves as a foundational concept for analytical exploration and practical application.

The improvement in production efficiency is closely linked to the growth rates of capital and labor productivity. This relationship stems from the producer's drive to achieve equilibrium, primarily motivated by the goal of profit maximization [23–25]. Specifically, this involves optimizing production outcomes from available resources, guided by the production function and current technologies. Here, the theoretical foundation involves technical progress, which is reflected in enhanced efficiency [26]. Moreover, the pursuit of efficiency gains has been intensified by the realization that competition extends beyond individual enterprises to entire supply chains [27,28].

The literature indicates that integrating resources within a single enterprise can be more efficient than conducting transactions through market mechanisms. Chandler [29] supports this theory by highlighting that internal organizational coordination not only boosts productivity, but also lowers costs and enhances profitability compared the results obtained through the use of market-based coordination [29]. The author asserts that economies of scale are not merely the result of expanding production within a single facility, but rather stem from leveraging internal networks and coordination across multiple plants within one enterprise [30]. Also, the ownership rights play a crucial role in efficiency. Alchian and Demsetz [31] contend that resource owners can enhance productivity and resource use efficiency through cooperative specialization. The integration of a company with its external environment is also essential for optimizing efficiency [32]. Integration involves both traditional logistics functions [33] and the removal of barriers between organizations [34]. As stated by Christopher [27], the quest for efficiency improvements has been significantly driven by the recognition that competition extends beyond individual enterprises to entire supply chains. The effective management of supply chains requires a strategic approach to coordinating activities both within and between organizations. Thus, integration emerges as a key factor for achieving superior results.

The interest of authors in supply chain integration has notably expanded, as highlighted by van der Vaart and van Donk [35]. A comprehensive review of the literature regarding enterprise integration with its environment reveals compelling evidence of a positive relationship between integration and efficiency. Frohlrich and Westbrook [36] and Vickery, Jayaram, Droge, and Calantone [37] acknowledge that higher levels of integration correlate with improved efficiency. This correlation is further supported by Leuschner, Rogers, and Charvet [38], who demonstrate a positive and significant link between supply chain integration (SCI) and firm performance, and by Prananta and Hidayat [39], whose research investigates the influence of supply chain integration, information sharing, and supplier relationships on operational efficiency in manufacturing companies across diverse industries. Additionally, Jarzębowski [40] provides evidence of the beneficial impact of integration on the efficiency of food processing enterprises within the agri-food sector. Moreover, the integration of blockchain technology into agri-based food supply chains can significantly improve transparency, accountability, and traceability, ultimately leading to the more efficient delivery and management of food products [41].

In their literature review, Fabbe-Costes and Jahre [42] conclude that there is broad consensus among scholars that stronger relationships and higher degrees of integration within supply chains generally lead to enhanced business performance. Studies highlight the positive impact of supply chain integration on organizational performance, emphasizing how it can lead to operational efficiency, cost reduction, and improved customer service. Despite this consensus, Ho, Au, and Newton [43] emphasize the need for detailed frameworks and methodologies to better describe and explain how integration practices influence company performance. Additionally, there remains a notable gap regarding the provision of detailed frameworks and concrete recommendations for enhancing supply chain integration [44]. These findings collectively reinforce the critical role of integration in enhancing operational efficiency and overall business performance.

3. Methodological Considerations

3.1. Supply Chain Integration Measurement

In the literature, three key aspects for assessing supply chain integration are identified: direction, scope, and level. The direction of integration pertains to the flow and coordination of information, materials, and resources across various stages of the supply chain. Achieving effective integration requires alignment and seamless communication with both upstream suppliers and downstream customers. The scope of integration determines which functions and processes are included in the integration efforts, influencing how comprehensively the supply chain is interconnected. The level of integration focuses on the depth of integration, from basic coordination and information sharing to more advanced collaborative planning and joint decision making.

Firstly, we suggest a distinction among the directions of integration (see Table 2).

In the academic literature, the integration of the supply chain is often conceptualized as a unique phenomenon that encompasses both upstream and downstream integration [37]. This perspective highlights the distinction between various integration approaches, such as top-down integration with suppliers and bottom-up integration with customers, as well as internal and external integration. Some studies have concentrated specifically on integration with suppliers. For instance, studies by Molinaro et al. [45], Handfield et al. [46], and Wagner and Krause [47] demonstrate that the effectiveness of supplier integration can vary, depending on factors like the concentration of the supply base. Certain types of supplier integration predominantly improve performance when the supply base is highly concentrated, whereas the impact on performance can differ, depending on the performance metrics considered [45]. Conversely, other researchers have focused on customer integration. Studies by Peppers and Rogers [48], Closs and Savitskie [49], and Fynes et al. [50] emphasize that a customer-focused strategy involves leveraging information to gain a competitive advantage and to drive growth and profitability. Effective customer integration requires businesses to tailor their approaches to different customer segments to maximize value. Moreover, some scholars argue that integrating both upstream and downstream players—encompassing both suppliers and customers—offers greater benefits compared to focusing solely on one integration direction [36,51].

Table 2. Criteria and description among directions of integration.

Author(s), Journal	Criteria/Aspects	Description
Molinaro, M.; Danese, P.; Romano, P.; Swink, M. [45]	Top-down integration with suppliers	Coordination and collaboration with suppliers of raw materials, goods, and services.
Peppers, D.; Rogers, M. [48]	Bottom-up integration with customers	Integration with customers who receive goods and services produced at various stages of the supply chain.
Patterson, M.G.; West, M.A.; and Wall, T.D. [52], Feyissa, T.T.; Sharma, R.R.K.; and Lai, K.-K. [53]	Internal integration	Coordination within a single company, encompassing various internal functions.
Ralston, P.M.; Blackhurst, J.; Cantor, D.E.; Crum, M.R. [54]	External integration	Integration with external partners beyond immediate suppliers and customers.

Source: own work.

In addition to upstream and downstream integration, it is crucial to consider internal and external integration within the supply chain context. While internal integration focuses on optimizing internal processes, external integration extends this coordination to external stakeholders. Both forms of integration are integral to enhancing overall supply chain performance and achieving a competitive advantage. According to Patterson et al. [52], internal integration involves aligning various internal functions and processes to enhance overall efficiency and performance. This internal coordination is particularly important because it mediates the positive effects of a company's product-market innovation strategy on its integration efforts regarding both suppliers and customers [53]. On the other hand, external integration involves the coordination between a company and its external partners, including suppliers and customers. Ralston, Blackhurst, Cantor, and Crum [54] describe how firms align their internal integration strategies with external integration efforts to optimize their supply chain operations. They argue that effective internal and external integration strategies significantly impact a firm's ability to respond to customer demands, which in turn influences both operational and financial performance. This bidirectional integration is considered more advantageous, as it enhances overall supply chain performance by fostering a more comprehensive and coordinated approach.

In addition to examining the direction of integration, various authors have also analyzed the scope of integration, which encompasses various areas of cooperation within the supply chain. The following areas of integration may be distinguished: material flow, planning and control, organization (type of cooperation), information flow, and product development (Table 3). By analyzing various scopes of integration, these authors provide a comprehensive view of how different areas of cooperation contribute to efficiency in the supply chain. It is crucial to understand and optimize the scopes in order to achieve better performance and enhance the competitive advantage. Financial flow is often omitted in these studies because the research focuses on specific operational aspects of supply chain management, such as material flow, planning, organizational culture, and information flow, to provide deeper insights into these critical areas.

Table 3. Criteria and descriptions regarding scopes of integration.

Author(s), Journal	Criteria/Aspects	Description
Sohrabpour, V.; Oghazi, P.; Olsson, A. [55]	Material flow	Strategies to bridge the gap between packaging design and development and supply chain requirements.
Blanchard, D. [56]	Planning and control	Application of the supply chain operations reference (SCOR) model to integrate business process reengineering with benchmarking, best practices, and process measurement for comprehensive supply chain project execution.
Braunscheidel, M.J.; Suresh, N.C.; Boisnier, A.D. [57]	Organization	Analysis of organizational culture characteristics that influence supply chain integration and delivery performance.
Qrunfleh, S.; Tarafdar, M. [58]	Information flow	Identification of IS application portfolios that enhance benefits from specific supply chain strategies, with tools for measuring SC strategies and IS strategies.
Kim, Y.H; Schoenherr, T. [59]	Product development/innovation	Examination of how customer and supplier integration activities, whether focused on products or processes, impact contract manufacturing returns.

Source: own work.

Thirdly, the level of integration is a critical aspect that reflects the extent and depth of integration activities within a supply chain. Researchers highlight that this level can be gauged by the range and sophistication of the integration practices employed. For instance, a significant level of integration can be achieved in planning and control through techniques like the multi-level supply control method [60]. The Global Supply Chain Forum (USA) provides a structured method for measuring integration levels, defining six types of relationships between partners, ranging from joint ventures to full vertical integration. These relationships include three partnership types—Partnerships I, II, and III—which represent low, medium, and high levels of integration, characterized by mutual trust, openness, and shared risk [61]. The use of more advanced and challenging practices indicate a higher level of integration.

The literature also reveals that integration levels can be influenced by the type of domination between partners [62]. Some approaches feature a dominant partner who exerts varying degrees of influence, depending on the scope of the agreement [62,63]. This influence can range from weak to strong, manifesting through mechanisms such as contract threats, control over production factors, or the potential withdrawal of know-how [62]. Moreover, the level of integration is closely linked to the integration of information technologies. The application of inter-organizational information and communication technologies across various operational areas—such as research and development (R&D), purchasing, production, sales, and market research—supports enhanced cooperation and coordination [64–66].

3.2. Selected Approaches for Efficiency Assessment of the Supply Chain

The supply chain should be regarded as a unified entity, and any measurement system must encompass the entire supply chain [67]. Despite this fact, a review of the literature reveals a notable scarcity of methods specifically designed for assessing efficiency within supply chain management. Within the framework of this paper, selected approaches to efficiency assessment in supply chains, as published in leading logistics and supply chain management journals, are examined. Each approach is analyzed and evaluated based on its efficiency assessment methods, the set of variables used, and the sample applied (see Table 4).

The most commonly used approach for measuring the efficiency of the supply chain is the comparison of financial indexes, such as the economic value added (EVA) and profit and market capitalization results [56]. The Global Supply Chain Forum in the USA has proposed a framework that aligns performance across each link in the supply chain, from suppliers to customers. This framework starts with the focal company and extends outward, addressing each link sequentially. This link-by-link approach facilitates the alignment of performance from the point of origin to the point of consumption, with the overarching goal of maximizing shareholder value for both the entire supply chain and individual companies [56].

Within the framework established by Hahn, Brandenburg, and Becker [68], a composite measure of total efficiency is proposed using the data envelopment analysis (DEA) method to identify the "best practice" supply chain. This approach incorporates multiple input and output indicators to capture operational supply chain performance, utilizing accounting-based top-level metrics aligned with value-based supply chain management [68]. The paper details how operational supply chain performance contributes to firm value. However, it is important to note that using the DEA method necessitates a larger sample size to reduce significant measurement errors and imprecise estimates, such as those arising from wide confidence intervals [69]. Additionally, a small sample size may result in many decision-making units (DMUs) being positioned on the efficiency frontier, which can artificially inflate the average efficiency ratio. In addition, due to the inability to conduct statistical tests, the selection of an appropriate model often relies on expert intuition [70].

Another method is the use of a multi-objective evolutionary algorithm (EA) employed to solve a bi-objective mixed-integer nonlinear programming model for supply chain design, incorporating location-inventory decisions and supplier selection. The model aimed to minimize costs across the entire supply chain while maximizing the overall equipment effectiveness from suppliers [71]. Other studies provided the analysis of deterministic and stochastic approaches. Within one study, Odeck and Brathen conducted a meta-analysis to examine the MTE estimates in the context of seaport studies [72]. The results compared fixed effects against a random-effects regression model, where the latter assumes that the individual study-specific characteristics matter, while the former assumes that there is one general tendency across all studies. The two-stage SMAA-DEA, proposed by Ang, Zhu, and Yang [73], combines the stochastic multicriteria acceptability analysis (SMAA) technique and data envelopment analysis (DEA) methodology. The developed model extends existing two-stage DEA models to handle uncertain or imprecise inputs, intermediate measures, and outputs using stochastic distributions [73]. The extended stochastic frontier model was developed by Jarzębowski [40]. The author proposed the use of the SFA method, extended using the supply chain integration degree measure (SCIDM). The last approach [40] is described in the next section of the paper.

Table 4. Evaluation of selected papers on efficiency of the supply chain.

Approach	Financial Indexes Approach	Deterministic Approach	Multi-objective Evolutionary Algorithm (EA)	Deterministic and Stochastic Approach	Deterministic and Stochastic Multicriteria Acceptability Analysis (SMAA)	Stochastic Approach in Connection to Integration Degree
Methods of efficiency assessment	Economic value added (EVA), profit and market capitalization	Data envelopment analysis (DEA)	Multi-objective evolutionary algorithm (EA) to solve a bi-objective mixed-integer nonlinear programming model for supply chain design with location-inventory decisions and supplier selection.	Data envelopment analysis (DEA) and the stochastic frontier analysis (SFA)	The two-stage SMAA-DEA stochastic multicriteria acceptability analysis (SMAA) technique and data envelopment analysis (DEA) methodology.	The SFA method, with extension with the supply chain integration degree measure (SCIDM), is used.
Variables/ Sample	The framework consists of seven steps: map the supply chain, analyze each link, develop profit and loss statements, realign supply chain management processes, align non-financial factors with profit and loss, compare across firms, and replicate US industry.	Large-scale longitudinal dataset of listed US companies (2007–2015) that covers 13 manufacturing industries. The implications of the 2008/2009 financial crisis for operational SC performance was also included.	The supply chain has four echelons: suppliers, plants, distribution centers, and retailers. The decision variables are the opening of plants and distribution centers and the flow of materials between the different facilities, considering a continuous review inventory policy.	Review of 40 studies on the TE measurement of seaports.	A total of 27 supply chains, comprising the supplier (process 1) and the manufacturer (process 2), are included for efficiency evaluation and ranking of two-stage supply chains (e.g., supplier–manufacturer) with stochastic criteria values.	The supply chain integration degree measure includes integration with both suppliers and customers.

Table 4. *Cont.*

Approach	Financial Indexes Approach	Deterministic Approach	Multi-objective Evolutionary Algorithm (EA)	Deterministic and Stochastic Approach	Deterministic and Stochastic Multicriteria Acceptability Analysis (SMAA)	Stochastic Approach in Connection to Integration Degree
Notes on applied approach	The link-by-link approach provides means for aligning performance from point-of-origin to point-of-consumption, with the overall objective of maximizing shareholder value for the total supply chain, as well as for each company.	The method captures operational SC performance using accounting-based top-level metrics that are consistent with the framework of value-based SCM. The paper outlines how and to what extent operational SC performance contributes to firm value.	The conflicting objectives include minimizing total costs on the entire chain, and maximizing a combined value of overall equipment effectiveness from suppliers. The potential for solving large-scale and complex combinatorial optimization problems using EAs is high.	The results compare fixed effects against a random-effects regression model, where the latter assumes that the individual study-specific characteristics matter, while the former assumes that there is one general tendency across all studies.	The developed model extends existing two-stage DEA models to handle uncertain or imprecise inputs, intermediate measures, and outputs using stochastic distributions. Variable process weights are allowed in the model, and any prior preference information on processes is not needed.	This is a three-step procedure: (1) the differentiation of integration direction (downward, upward, or in both directions); (2) the determination of the range of integration, i.e., areas of cooperation; (3) the analysis of the level of integration, which can be described as the degree of development of integration activities, in both directions, for the supplier (ILS) and the customers (ILC), respectively.
Critics/Research gaps	An advanced, complex approach. Possible problems with the access/collection of datasets to assess the performance of several supply chain participants might occur.	Small number of analyzed units, which is same for both the nonparametric method and the DEA.	The model should be extended to other industrial applications, such as the manufacturing of electronics and appliances. For future studies related to the model, stochastic values can be introduced in facility capacities (dispatch and inventory), transportation costs, delivery times, etc.	This result is in contrast to those of other studies which showed that panel data produce higher MTE scores than cross-sectional data.	The relationship between the chain and the processes in two-stage and general SCs requires further study. The application to more real-world cases, such as business firms, government agencies, and educational institutions, is needed.	Possible problems with the access/collection of a detailed dataset to assess performance might occur.

Source: own work.

3.3. The SFA Method Extended by an External Variable—The Supply Chain Integration Degree Measure

A company, as understood within the neoclassical economic framework, can be characterized by a production function [74]. This function forms the cornerstone of theoretical analyses in neoclassical economics, serving as a fundamental representation of the input–output relationships within an enterprise. It reflects the state of technology, encompassing applied techniques, organizational methods, knowledge, and experience [75]. One of the stochastic methods grounded in the production function is stochastic frontier analysis (SFA), which allows for the consideration of statistical noise. The performance-focused modeling in this study utilizes the SFA method due to its widespread application in global research and its suitability for samples with high randomness, such as those in the food sector. The SFA method, which relies on the input–output relationship function, enables efficiency comparisons among sampled entities by making assumptions about their performance. As a parametric approach, the SFA method necessitates assuming a specific functional form for the input–output relationship beforehand [75]. Among the models frequently employed in empirical studies is the Cobb–Douglas function [76]. However, the suitability of the Cobb–Douglas model should be tested against that of a less restrictive functional form, such as the translog function [77].

Consequently, this study examines two functional forms describing the input–output relationship: the Cobb–Douglas model (Equation (1)) and the translog model (Equation (2)). Comparison of the selected functional forms is carried out based on the likelihood ratio test statistics. The LR statistics are presented in the following format: $LR = -2[\ln L(R) - \ln L(N)]$, where: $lnL(R)$—logarithm of the maximum likelihood value in the restricted model; $lnL(N)$—logarithm of the maximum likelihood value in the non-restricted model. The frontier models under consideration take the following forms:

$$lny_i = b_0 + b_1 lnx_{1i} + b_2 lnx_{2i} + v_i - u_i \tag{1}$$

and

$$lny_i = b_0 + b_1 lnx_{1i} + b_2 lnx_{2i} + \frac{1}{2}\sum_{j=1}^{2}\sum_{l=1}^{2} b_{jl} lnx_{ij} lnx_{il} + v_i - u_i \tag{2}$$

where:

i—index indicating objects i = 1, . . ., I, where I is the number of objects in a sample;
j—index indicating inputs j = 1, . . ., l;
y_i—output of an object i;
x_{ij}—input j of an object i;
β—vector of parameters to be estimated;
v_i—random variable representing the random error, i.e., statistical noise;
u_i—a positive random variable associated with technical efficiency (TE).

The efficiency ratio in the context of the stochastic frontier function is determined by the relationship between the observed output (denoted as y in Equation (1)) and the maximum possible output achievable in an environment characterized by exp(vi) (value y*). $exp(vi)$ (denoted as y^*). This relationship can be expressed as follows, based on the transformed function in Equation (1):

$$TE_i = \frac{y_i}{y_i^*} = \frac{\exp(b_0 + b_1 lnx_{1i} + b_2 lnx_{2i} + v_i - u_i)}{\exp(b_0 + b_1 lnx_{1i} + b_2 lnx_{2i} + v_i)} \tag{3}$$

Based on Equation (3), the value of the technical efficiency (TE) ratio ranges from 0 to 1. A value of 1 indicates that the entity is technically efficient, while a value less than 1 (TE < 1) indicates a shortfall of observed output from the maximum feasible output, signaling inefficiency in an environment characterized by $exp(v_i)$. It is assumed that u_i follows a limited-normal distribution truncated at zero, which is described by the following expression:

$$u_i \sim N^+\left(\mu, \sigma_u^2\right) \quad (4)$$

In the context of SFA, it is possible to assess the impact of exogenous variables (not included in the adopted function) on the level of efficiency, such as the variable u_i [78,79]. The influence of potential determinants of technical efficiency can be estimated through the parameter μ in the truncated normal distribution. The parameter μ is assumed to depend on some variable vector, according to the following relationship [80]:

$$\mu_i = \delta_0 + \sum \delta_k z_{ki} \quad (5)$$

where:

z_i—independent variables of an i-th object associated with inefficiency (it should be noted that estimation of the parameters of the vector z_i determines the strength of influence of a given variable on increasing the inefficiency level of the analyzed group);

δ—vector of parameters of the inefficiency variables.

Within the framework of the paper, vector z_i is represented by the variable showing integration in the supply chain. The authors indicate that the efficiency of an enterprise can be increased if there is a strong cooperation within the entire chain. In the context of this, a measure showing the degree supply of chain integration was constructed. The variable SCIDM (supply chain integration degree measure) includes integration with both suppliers and customers. The construction of the measure of supply chain integration is as follows:

$$SCIDM = \sum_{i=1}^{k}\sum_{j=1}^{n} IRS_i ILS_j + \sum_{i=1}^{k}\sum_{j=1}^{n} IRC_i ILC_j \quad (6)$$

where:

SCIDM—supply chain integration degree measure;
IRS—supplier integration range;
ILS—supplier integration level;
IRC—customer integration range;
ILC—customer integration level;
i—areas of cooperation, where $i \in (1, \ldots, k)$;
j—integration activity, where $j \in (1, \ldots, n)$.

The literature often emphasizes key aspects of supply chain integration, which were utilized in constructing the supply chain integration degree measure (SCIDM). The first aspect involves the direction of integration, distinguishing between downward integration with suppliers, upward integration with customers, or integration in both directions. The second aspect examines the scope of integration, focusing on different areas of cooperation. Subsequently, the level of integration is analyzed, described as the degree of development of integration activities for both suppliers (ILS) and customers (ILC) within the identified cooperation areas (IRS and IRC). This level is measured by the number of activities in these areas and the number of integration practices, categorized as low, medium, or high. A detailed description of the variables included in the SCIDM is presented in the work of Jarzębowski [40]. The integration assessment was based on survey data from processing enterprises in three food subsectors (milk, meat, and fruit and vegetable processing) across Poland.

The SCIDM was included in the model of efficiency measurement in Equation (3); thus, we conclude, based on Equation (5) that:

$$\mu_i = \delta_0 + \delta_1 SCDIM_i + e_i \quad (7)$$

Additionally, other factors not included in the initial analysis could influence efficiency, which is why the error term e_i was incorporated into the model. It is important to highlight that the estimation of the parameter δ_1 measures the impact of the variable SCDIM on the level of inefficiency within the examined group. Specifically, a negative value for δ_1 suggests a positive effect, while a positive value indicates a negative impact on efficiency.

4. Empirical Visualization Using the Extended SFA Method

4.1. Dataset

To visualize the theoretical concept of integration concerning one of the pillars of sustainable development, namely the economic aspect, the food sector was used. The food economy represents one of the most vital and intricate segments within the national economy, encompassing the entire spectrum of material production directly and indirectly associated with food production and distribution [81]. It includes the production of agricultural means, agricultural practices, and the food industry. Food production and distribution are crucial components of the agribusiness sector. The movement of food from farmers to consumers is orchestrated via the interconnected links of agribusiness, forming what is commonly referred to as the food supply chain, in such a way that food supply chain management follows a "farm to fork" structure [81].

The supply chain for food products can be defined as a collaboration among various entities within agriculture, including producers, intermediaries (traders), processors, manufacturers, service providers, and customers. It involves the flow of agricultural and food products, information, and financial resources [82]. The food supply chain encompasses activities such as procurement, processing, distribution, food services, and retail trade, and it continually evolves in response to transformations and economic demands. However, the food supply chain exhibits unique characteristics, including temporal imbalances between supply and demand, stringent quality requirements, and the exchange of quality-related information. Notably, food products are subject to specific safety regulations designed to safeguard the end consumer. Consequently, numerous standards and rules impact the operations of enterprises within the food supply chain, particularly those related to food traceability, safety, sustainability, and quality within limited time frames [2].

An attempt was made to verify the raised theoretical issues and the developed methodological concept presented in this article. The efficiency assessment was carried out on the basis of data from the financial statements of processing enterprises from three food subsectors (i.e., milk, meat, fruit and vegetable processing) across Poland. A dataset from six periods was used (see Table 5). The source of data was the Monitor Polski B, in which financial statements are published. The division of the food sector into three subsectors was performed due to the different production technologies used in each of them. It is important to note that the choice of the research area and the research period was not critical; data selection was based on data availability. The aim was to confirm the validity of the conceptual framework developed in earlier sections of the article.

Table 5. The number of analyzed companies in selected subsectors within the six periods.

Subsector	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
milk processing	137	160	103	155	141	122
meat processing	202	210	195	208	204	197
fruit and vegetable processing	138	148	125	130	132	119

Source: own work.

From the milk processing subsector, we incorporated 103–160 companies, while 195 –210 companies and 119–148 companies were analyzed from the meat processing and fruit and vegetable subsectors, respectively; we also included in the sample various SMEs (micro, small, medium) and large enterprises.

In the analysis, the production frontiers are constructed using a model with a single output and two inputs. According to the literature on efficiency assessment, fixed assets (denoted as x_1) and operating costs (denoted as x_2) are included as input variables. Net revenues from the sales of goods and materials (denoted as y) are considered as the output. While profit could theoretically be included as an additional output, it was excluded from the model due to its strong correlation with operating costs. Consequently, net revenues from sales of goods and materials remain as the sole output variable in the model [83].

4.2. Assessment of Integration and Efficiency

As discussed earlier in the paper, selecting an appropriate functional form is essential in the stochastic frontier analysis (SFA) method. Among the various functional forms, the translog and Cobb–Douglas production functions are frequently utilized in empirical research, including frontier analyses [84]. For this study, both the Cobb–Douglas and translog production functions were considered. The decision to use a specific functional form was guided by likelihood ratio tests. The Cobb–Douglas function, with its parameter constraints (Equation (1)), was found to more accurately describe the input–output relationships in the context of this study. Consequently, the empirical results presented are based solely on the Cobb–Douglas function. The variable representing the degree of integration of the analyzed entities (denoted as SCDIM, as discussed previously) was incorporated into the models. Each model was constructed individually for each subsector and period, with the SCIDM calculated separately for each period.

Table 6 presents the maximum likelihood estimates of the parameters for the Cobb–Douglas function. The parameters b_0, b_1, and b_2 pertain to the Cobb–Douglas function (Equation (1)), while δ_0 and δ_1 represent the function illustrating the impact of supply chain integration on efficiency (Equation (7)). The parameters b_0, b_1, and b_2, estimated in each model, are statistically significant at a level below 0.05.

Table 6. The maximum likelihood estimates of the Cobb–Douglas function parameters.

Sector	Variable/Parameter	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
dairy processing	$Intercept/b_0$	0.74	−0.03	2.47	1.08	−0.95	2.19 **
	X_1/b_1	0.24 ***	0.20	0.47	0.25 *	0.24 ***	0.22 ***
	X_2/b_2	0.57 ***	0.70 ***	0.26 *	0.57 ***	0.68 ***	0.44 ***
	$Intercept/\delta_0$	4.99 ***	3.62 ***	5.68	4.70 ***	3.57 ***	4.00 ***
	$SCIDM/\delta_1$	−0.03 ***	−0.01 ***	−0.03 ***	−0.02 ***	−0.03 ***	−0.03 ***
meat processing	$Intercept/b_0$	2.32 ***	0.48	2.14 **	1.74 **	1.27 *	1.29
	X_1/b_1	0.16 **	0.20 ***	0.30 ***	0.29 ***	0.27 ***	0.31 ***
	X_2/b_2	0.44 ***	0.58 ***	0.35 ***	0.40 ***	0.46 ***	0.41 ***
	$Intercept/\delta_0$	3.06 ***	3.33 ***	3.39 ***	3.64 ***	4.00 ***	3.62 ***
	$SCIDM/\delta_1$	−0.03 ***	−0.05 ***	−0.03 ***	−0.04 ***	−0.05 ***	−0.04 ***
fruit and vegetables processing	$Intercept/b_0$	−1.93 **	−1.43	−1.32	0.47	−0.16	0.49
	X_1/b_1	0.27 ***	0.14 ***	0.33 ***	0.27 ***	0.11	0.26 ***
	X_2/b_2	0.74 ***	0.83 ***	0.66 ***	0.56 ***	0.75 ***	0.57 ***
	$Intercept/\delta_0$	3.72 ***	2.67 ***	4.99 ***	3.93 ***	3.88 ***	4.40 ***
	$SCIDM/\delta_1$	−0.03 **	−0.02 *	−0.06 *	−0.03 **	−0.02 **	−0.02 ***

Significance codes: 0.01—***; 0.05—**; 0.1—*. Source: own calculations.

The examination of the stochastic frontier analysis (SFA) results reveals significant insights into the impact of supply chain integration (SCIDM) on technical efficiency across various sectors. By evaluating the effects of supply chain integration on technical efficiency, particularly through the SCIDM variable, we gain insights into how improved integration practices can lead to more sustainable outcomes. This examination not only highlights the varying impacts across different industries, but also underscores the significant role that effective supply chain management plays in advancing sustainability by promoting resource conservation and reducing environmental impacts.

In the analysis of supply chain integration's impact on efficiency, distinct patterns emerge across different sectors, reflecting varied implications for sustainability. The dairy sector demonstrates a consistently negative δ_1 parameter, signifying that enhanced supply chain integration directly correlates with increased operational efficiency. This consistent negative relationship across periods underscores the profound influence of integration on efficiency within the dairy industry. Enhanced integration in the dairy sector facilitates better coordination and management of the complex logistics inherent in dealing with perishable goods. This optimization translates into reduced waste, lower energy consumption, and improved resource utilization, all of which align closely with sustainability objectives. Efficient management in this sector not only lowers operational costs, but also diminishes environmental impacts, reinforcing the sector's commitment to sustainable practices.

Conversely, the meat sector exhibits a more variable δ_1 parameter, with negative values indicating a beneficial impact of supply chain integration on efficiency, though the extent of this effect fluctuates over time. This variability can be attributed to shifting market conditions, diverse operational strategies, and external influences affecting the meat supply chain. Such fluctuations imply that while supply chain integration positively affects efficiency, the degree of this impact is subject to change. This inconsistency may lead to a less stable contribution to sustainability compared to that noted in the dairy sector. Apart from this, improved efficiency through integration in the meat sector still supports sustainability by potentially reducing resource wastage and operational inefficiencies, albeit in a less uniform manner.

In the fruit and vegetable sector, the δ_1 parameter also generally shows negative values, though the significance of these results is less consistent. This variability suggests that the impact of supply chain integration on efficiency is more erratic in this sector, likely due to the perishable nature of the products and the diverse logistical challenges faced by this industry. While integration improves efficiency, the sector's distinct characteristics lead to less predictable outcomes. Nevertheless, greater efficiency achieved through integration can contribute to sustainability goals by optimizing resource use and reducing environmental impacts, even if the benefits are not as uniformly distributed across periods.

Overall, the dairy sector demonstrates the most substantial alignment between supply chain integration and sustainability, driven by its pronounced improvements in efficiency. Integration in this sector leads to considerable gains in operational performance, resource conservation, and environmental sustainability. This enhanced efficiency promotes better resource management and reduced carbon emissions, underscoring the sector's potential for achieving sustainability goals more effectively compared to that of the meat and fruit and vegetable sectors. Thus, while integration benefits all sectors, its impact on sustainability is the most robust in the dairy sector due to the significant improvements in efficiency and resource utilization observed.

The examination of the stochastic frontier analysis (SFA) results reveals significant insights into the impact of supply chain integration (SCIDM) on technical efficiency across various sectors. These findings are corroborated by existing studies that highlight the benefits of supply chain integration in enhancing efficiency and sustainability outcomes. For instance, Flynn et al. [10] emphasize that supply chain integration leads to improved operational performance by facilitating better coordination and resource utilization. Similarly, Frohlich and Westbrook [36] demonstrate that closer integration with suppliers and customers significantly enhances operational efficiency and responsiveness.

5. Discussion

5.1. Limitation of the Study

This study, while contributing valuable insights into the relationship between supply chain integration and efficiency, has several limitations that warrant consideration. Firstly, the research is constrained by the scope of the empirical data, which predominantly reflects the conditions within the selected sectors and periods. This limitation may affect the generalizability of the findings across different industries or geographic regions. The dataset, while comprehensive, may not capture the full spectrum of variability in supply chain practices and efficiency measures.

Secondly, the study's methodological approach, while robust, has inherent limitations related to the stochastic frontier analysis (SFA) and the supply chain integration degree measure (SCIDM). The SFA method requires a specific functional form for the production function, which may not fully capture the complexities of supply chain operations. The SCIDM, although a valuable tool for assessing integration levels, may not encompass all dimensions of supply chain relationships, such as informal collaborations. These methodological constraints highlight the need for caution when interpreting the results, underscoring the importance of the ongoing refinement and validation of the measurement tools used in this research.

5.2. Development of Future Studies

Future research can build upon this study by addressing its limitations and exploring new dimensions of supply chain integration and efficiency. A promising avenue includes the broadening of the empirical scope by including a wider range of industries and geographic regions. This expansion would enhance the generalizability of the findings and offer a more comprehensive understanding of how supply chain integration impacts efficiency across diverse contexts.

The stochastic frontier approach (SFA) is valuable for assessing efficiency within supply chains. However, to fully harness its potential for informing policy and management decisions in the context of sustainability, it is crucial to extend its scope to encompass environmental and social aspects. Therefore, there is a need to develop a modeling tool that incorporates environmental and social variables into supply chain assessments. This tool must integrate metrics for evaluating resource efficiency, waste generation, carbon footprint, labor conditions, community impacts, and social equity. By incorporating external factors, such as compliance with environmental regulations, initiatives for social responsibility, and practices for engaging stakeholders, the extended modeling approach can offer a more comprehensive evaluation of sustainability performance. Moreover, modeling environmental and social aspects alongside efficiency metrics can elucidate the way in which supply chain integration influences not only economic outcomes, but also environmental stewardship and social welfare.

6. Conclusions

This study advances our understanding of how supply chain integration contributes to efficiency and sustainability within the food sector. The paper provides a discussion of various methods for evaluating integration throughout the supply chain and explores approaches for assessing efficiency within the supply chain. Empirical validation conducted in the study using the parametric stochastic production function (SFA), augmented by the supply chain integration degree measure (SCIDM), confirmed a positive relationship between integration levels and efficiency across different periods and subsectors of the food industry. These findings substantiate both the theoretical framework proposed and the methodological approach employed in the article.

Furthermore, the paper provides a robust theoretical and analytical foundation for understanding how integration impacts efficiency within the food supply chain, expanding current perspectives on sustainability. While the existing literature provides some foundational understanding of how integration influences company performance, this study provides a comprehensive analysis that links integration to efficiency and, by extension, to sustainability. This holistic approach fills a significant gap in the current knowledge and sets the stage for further research aimed at developing metrics to quantify the impact of food supply chain integration on sustainable development.

The relationship between supply chain integration, efficiency, and sustainability is pivotal in advancing our understanding of sustainable practices within the food sector. This study highlights that higher levels of supply chain integration are closely linked to increased operational efficiency, which in turn plays a critical role in achieving sustainability goals. The empirical results derived from the parametric stochastic frontier analysis (SFA) and the supply chain integration degree measure (SCIDM) reveal that enhanced integration fosters a more efficient use of resources, minimizes waste, and reduces carbon footprints. These efficiency improvements not only lead to cost savings, but also align with broader environmental and social sustainability objectives.

Efficient supply chain practices contribute significantly to sustainability by optimizing resource utilization and reducing the environmental impact associated with production and distribution processes. For instance, in sectors such as the dairy industry, where integration consistently improves efficiency, the resultant reductions in waste and energy consumption are directly beneficial to environmental sustainability. Similarly, although the impacts are more variable in the meat and fruit and vegetable sectors, the integration-driven efficiency gains still support sustainability through better resource management and lower operational impacts. By connecting efficiency with sustainability goals, this study underscores that effective supply chain integration is not merely a matter of operational optimization but a fundamental component of sustainable development. It emphasizes that achieving higher efficiency through integration can drive significant advancements in sustainability, thus reinforcing the need for strategic integration as a core element of sustainable business practices.

The implications of this research are broad and relevant to various stakeholders, including researchers, business leaders, policymakers, investors, and industry associations. Researchers can use the theoretical and methodological insights provided in this work to enhance their understanding of how integration improves supply chain efficiency. Business professionals have the opportunity to apply these insights to refine their supply chain strategies for greater effectiveness. Policymakers can draw on the empirical evidence to develop regulatory frameworks that encourage practices contributing to overall sustainability. For investors and industry associations, the findings offer guidance for making informed investment decisions and establishing industry standards that support increased efficiency as a key component of sustainable practices.

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