logistics

Article

Assessing the Impact of Healthcare 4.0 Technologies on Healthcare Supply Chain Management: A Multi-Criteria Evaluation Framework

Ayoninuoluwa Oluwadare [1], Busola Dorcas Akintayo [2,*], Olubayo Moses Babatunde [2,3] and Oludolapo Akanni Olanrewaju [2]

[1] Aetna Inc., 151 Farmington Avenue, Hartford, CT 06156, USA; ayoninuoluwa@gmail.com
[2] Department of Industrial Engineering, Faculty of Engineering and the Built Environment, Durban University of Technology, Durban 4001, South Africa; olubayobabatunde@gmail.com (O.M.B.); oludolapoo@dut.ac.za (O.A.O.)
[3] Department of Electrical Electronics Engineering, University of Lagos, Lagos 100213, Nigeria
* Correspondence: olagunjubusola52@gmail.com

Abstract: *Background*: Healthcare 4.0 has transformed supply chain management in the healthcare sector, but there is a lack of comprehensive frameworks to evaluate the impact of Healthcare 4.0 technologies on sector operations, particularly in developing countries. *Methods*: This study introduces a multi-criteria framework that synergically combines the techno-economic implications of Healthcare 4.0 technologies to improve healthcare supply chain management. The proposed approach innovatively integrates fuzzy VIKOR and Entropy methods to handle data vagueness and uncertainty, using data collected from healthcare supply chain specialists in Lagos, Nigeria. *Results*: The developed framework identifies the most and least critical technical and economic parameters for Healthcare 4.0 implementation in healthcare supply chain management. It also determines the suitability of different Healthcare 4.0 technologies for supply chain management in the healthcare sector. *Conclusions*: The main innovation of this study lies in the development of a comprehensive and context-specific framework for evaluating Healthcare 4.0 technologies in healthcare supply chains. The framework offers a new perspective on technology evaluation and provides practical insights for decision-makers. The findings contribute to advancing knowledge and practice in this field, promoting the proper adoption of Healthcare 4.0 technologies in healthcare, particularly in developing countries.

Keywords: decision science; developing countries; Healthcare 4.0; multi-criteria; supply chain

check for updates

Citation: Oluwadare, A.; Akintayo, B.D.; Babatunde, O.M.; Olanrewaju, O.A. Assessing the Impact of Healthcare 4.0 Technologies on Healthcare Supply Chain Management: A Multi-Criteria Evaluation Framework. *Logistics* **2024**, *8*, 44. https://doi.org/10.3390/logistics8020044

Academic Editors: Eduard Sevtsenko and Ibrahim Raji

Received: 31 January 2024
Revised: 7 March 2024
Accepted: 27 March 2024
Published: 15 April 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Technology explosion has redefined service delivery and quality across the globe, especially in developed countries where extensive research has been reported on service system management because of unending customer demand [1,2]. Their demand has made business owners consider business analytics and development as an integral aspect of business innovations. The innovation is driven by the novel works that have made Industry 4.0 a buzzword among tech-savvy experts in service systems. Healthcare 4.0 did not only change business outlooks, but it also increased business sustainability and profitability through the appropriate deployment of technologies that addressed business needs [3,4].

The optimization of Healthcare 4.0 technologies is data-driven because of business uniqueness and investment capacity. Businesses with good record-keeping practices are therefore pioneering the implementation of different Healthcare 4.0 technologies, and this has given them a cutting-edge advantage over businesses that rely on the traditional approach of service delivery to clients, especially in the healthcare sector [5–7]. This sector relies heavily on technologies to save lives and maintain goodwill for their businesses, especially in developed countries. Hence, this sector is continuously experiencing the induction of technologies that have optimized service delivery and quality to clients [8].

Service delivery and quality measurement in the healthcare sector is difficult because of the vagueness and ambiguity in the data required from clients to assess the impact of Industry 4.0 implementation in this sector [9]. Expanding the scope of the evaluation requirements to techno-economic parameters is an issue because of the lack of literature on this subject matter. This knowledge gap serves as motivation for this article. State-of-the-art Healthcare 4.0 technologies for supply chain management have shown sparse information on empirical analysis of technologies' evaluation in the healthcare sector [10]. Several factors are responsible for this incident. First, the issue of technical criteria that are significant to Industry 4.0 implementation regarding supply chain management in healthcare has rarely been considered. Second, the literature shows that similar trends exist in terms of the significance of the economic criteria for Healthcare 4.0 technology deployment in the healthcare sector. Lastly, limited information exists about which Healthcare 4.0 technology impacts the healthcare sector the most in developing countries. The lack of empirical solutions to the above issue is another motivation for this study. In this study, we provided a solution to the above-mentioned issues using a multi-criteria approach. Hence, this study aimed to develop a framework for evaluating the impact of Industry 4.0 technologies in healthcare supply chain management using a developing country as a case study. This study will answer the following research questions:

- RQ1: What are the most important technical and economic indicators for assessing the impact of Healthcare 4.0 technologies on healthcare supply chain management in developing countries?
- RQ2: How suitable are different Healthcare 4.0 technologies for improving supply chain management in the healthcare sector?
- RQ3: How can the proposed framework advance knowledge and practice in adopting Healthcare 4.0 technologies in healthcare supply chains, particularly in developing countries?

In the proposed framework, the fuzzy entropy method was used to determine the significance of the techno-economic parameters for evaluating selected Industry 4.0 technologies. The impact of these technologies on healthcare was evaluated using a fuzzy VIKOR method. In addition, this study used a Technique for Order Preference by Similarity to Ideal Solution (TOPIS) to compare the VIKOR results. The main contributions of this research are twofold. First, the study proposes a comprehensive framework for evaluating the impact of Healthcare 4.0 technologies on supply chain management in the healthcare sector. This framework integrates both technical and economic criteria, allowing for a holistic assessment of these technologies. Second, the study demonstrates the application of this framework through a case study in a developing country context, providing valuable insights into the challenges and opportunities of implementing Healthcare 4.0 in resource-constrained settings.

This article is structured as follows: Section 2 provides a comprehensive literature review on applying Healthcare 4.0 technologies in supply chain management. Section 3 describes the materials and methods used in this study, including the problem statement, the proposed framework, and the multi-criteria decision-making techniques employed. Section 4 presents a case study demonstrating the application of the proposed framework in the context of a developing country. Section 5 discusses the results and their implications for healthcare supply chain management. Finally, Section 6 concludes the article and offers suggestions for future research.

2. Literature Review

The COVID-19 pandemic has resulted in unparalleled disturbances to various industries, with the healthcare domain encountering noteworthy disruptions. Keeping the health system running was vital, which meant having a steady and timely supply of necessities like masks and ventilators. Post-COVID-19 pandemic, more than ever before, healthcare 4.0 has been identified as an essential framework for ensuring the efficiency of healthcare delivery globally. Healthcare 4.0 refers to the use of Industry 4.0 technologies in the healthcare industry, such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and blockchain [11]. These technologies attempt to improve healthcare services' efficiency, efficacy, and quality by allowing for real-time data collecting, analysis, and decision-making. Several Healthcare 4.0 technologies have been highlighted as having significant potential for enhancing supply chain management in the healthcare industry. These include IoT-enabled inventory management systems that allow for real-time tracking and monitoring of medical supplies [12], AI-powered demand forecasting and supply planning tools that can optimize inventory levels and reduce waste [13], Blockchain-based solutions for ensuring the integrity and traceability of medical products throughout the supply chain [14], and big data analytics for identifying and mitigating supply chain risks, such as disruptions and quality issues [15]. This section discusses various studies that have been dedicated to the improvement of the healthcare delivery supply chain, especially using Industry 4.0.

Recent studies have explored the potential benefits and challenges of implementing Healthcare 4.0 technologies in supply chain management. Boz [16] examined how to choose a sustainable supplier during the pandemic while taking Logistics 4.0 into consideration. Fuzzy multi-criteria decision-making techniques were used to evaluate the direct effects of the pandemic on the health sector. The fuzzy Additive Ratio Assessment Method was used to rank alternative providers, and the Fuzzy Best-Worst Method was used to determine criteria weights. A thorough sensitivity analysis examined supply chain weaknesses and offered insights into how the health system survived difficult times like COVID-19.

Hossain and Thakur [17] focused on determining the most important variables for adopting Industry 4.0 in the healthcare supply chain (HCSC), specifically during health outbreaks. The study used fuzzy-AHP and fuzzy-DEMATEL methodologies to determine the order of importance for various criteria. The findings reveal that HC logistics management is the highest priority, followed by integrated HCSC, sustainable practices, innovation, institutional perspectives, competitiveness, social aspects, and economic issues. The findings offer useful information for policymakers and health administrators seeking to improve operational performance in healthcare facilities. Chatterjee et al. [18] examined the effects of Industry 4.0 on Healthcare Supply Chain Management (HCSCM) after the COVID-19 pandemic, considering the moderating role of environmental dynamism. The research examined the period following the implementation of advanced technologies such as Industry 4.0. It utilized a conceptual model that has been validated using the PLS-SEM approach with 312 respondents from the HCSCM field. The results demonstrated a notable enhancement in the performance of HCSCM due to the implementation of Industry 4.0. The study emphasized the significant influence of environmental dynamism on the relationship between Industry 4.0 technology adoption and healthcare supply chain management (HCSCM).

The study conducted by AbdelMouty et al. [19] examined the effects of Industry 4.0 on the Healthcare Supply Chain (HCSC) sector, with a particular focus on the advantages of automation and digitalization. The effectiveness of an HCSC supplier was evaluated using single-valued neutrosophic sets and the MABAC approach across 18 criteria and nine alternatives. The results have verified the efficacy of the framework in examining the Internet of Things (IoT) and Industry 4.0's impact on the Healthcare Supply Chain (HCSC), providing significant insights for enhancing supply chain operations. Luz et al. [10] introduced a problem-focused approach that utilizes algebraic operations from Quality Function Deployment's House of Quality to determine the order of importance for integrating Industry 4.0 (I4.0) technology in hospitals. The approach considered the significance of healthcare value chain issues and the present degree of I4.0 implementation. The strategy's effectiveness in promoting systemic integration of Industry 4.0 (I4.0) is shown through case studies conducted in a public hospital in Brazil and a private hospital in India. These findings provide valuable insights for healthcare companies in prioritizing their digitization efforts.

Daú et al. [20] proposed a theoretical framework for the Healthcare Sustainable Supply Chain 4.0, which combines the transition towards a circular economy and the implementation of corporate social responsibility within the context of Industry 4.0. The empirical data obtained from a healthcare institution in Rio de Janeiro have demonstrated the potential of glass structures in providing resources. The study revealed that corporate social responsibility establishes a connection between healthcare facilities and sustainable practices while also improving the implementation of smart technologies. The utilization of the Internet of Things and other services enhanced the benefits of sustainable practices, making it easier to shift from a linear to a circular model in the healthcare supply chain 4.0. Rehman and Ali [21] emphasized resilience methods for healthcare supply systems, acknowledging their vital significance in human survival. The fuzzy Analytical Hierarchy Process (AHP) was used for criteria weighting, and the fuzzy TOPSIS was used for risk prioritizing. According to the research, the most important resilience strategies are Industry 4.0, multiple sourcing, risk awareness, agility, and global diversification. The unique multi-criteria decision-making (MCDM) technique aided in prioritizing options in healthcare supply chains with severe, probable, and lengthy recovery risks.

Fatorachian and Kazemi [22] conducted a comprehensive assessment of existing literature to examine the potential impact of Industry 4.0 technologies on the operation of supply chains. Advocates assert that these technologies facilitate a comprehensive approach to supply chain management, resulting in enhanced integration, information dissemination, and transparency. The authors propose that Industry 4.0 has the potential to improve significantly specific supply chain activities, including procurement, production, inventory management, and retailing. This improvement can be achieved by integrating processes, digitization, automation, and advanced analytics.

The impact of Healthcare 4.0 (H4.0) technologies and implementation barriers on hospital performance was examined by Tortorella et al. [23]. Using multivariate statistical methods, they analyzed data from a cross-sectional study involving 181 hospital administrators. By categorizing challenges and H4.0 technologies into bundles, the study demonstrates that adopting H4.0 technologies positively impacts hospitals' performance. Additionally, the interplay between barriers and technologies substantially affects performance enhancement. The results of this study offer valuable insights for managers to proactively identify and resolve challenges that may arise during the implementation of H4.0. This will facilitate their endeavors to improve performance and ensure the provision of cost-effective, high-quality healthcare.

The study conducted by Vishwakarma et al. [24] examined the impact of blockchain technology (BCT) on the efficiency of healthcare supply chain management (HSCM) amidst the COVID-19 pandemic. Hypotheses were developed to examine the interrelationships among BCT, Healthcare Sustainable Supply Chain Practices (HSSCP), Healthcare Supply Chain Performance (HSCP), and Stakeholders' Involvement (SI) practices. They administered Structural Equation Modeling to analyze healthcare professional data. The results indicate that BCT has a beneficial effect on SI and HSSCP practices, which subsequently positively influence HSCP performance. This underscores the advantages of implementing BCT-enabled HSSCP in the fight against pandemic challenges.

In their study, Kim and Lee [25] examined the effects of digitalization on the performance of supply chains within the healthcare manufacturing sector, with social capital as a mediating factor. Data was gathered from healthcare manufacturing companies in South Korea and subsequently subjected to analysis via structural equation modeling. According to the findings, digitalization positively impacted social capital formation, which positively impacted supply chain performance. The authors underscored the significance of strategic alliances and prompt dissemination of information in supply chains for efficient product and service flow management.

AbdelMouty et al. [19] investigated the impact of the Internet of Things (IoT) and Industry 4.0 on the Healthcare Supply Chain. To deal with uncertainty and numerous criteria and features, they created a framework that combined a single-valued neutrosophic set with MCDM. The study applied 18 criteria and nine vendors to the HCSC. The authors stressed the relevance of HCSC awareness in the contemporary complex and ever-changing global economy and the ability of IoT and Industry 4.0 technologies to improve operations by automating mundane processes and decreasing human error. The findings showed that the suggested framework efficiently handled ambiguous data and produced more effective results when examining the impact of IoT and Industry 4.0 in HCSC.

Tortorella et al. [26] investigated how ten Healthcare 4.0 (H4.0) digital technologies affect four resilience abilities (monitor, predict, respond, and learn) in hospitals. The study surveyed 109 resilient healthcare and H4.0 professionals from emerging and developed nations and examined the results using univariate and multivariate statistical methods. The study identified four H4.0 digital technologies that significantly impact the four resilience abilities: remote consultations and real-time plan of care development, digital non-invasive care, interconnected medical emergency support, and digital platforms for collaborative sharing of patient data and information. These technologies can lessen reliance on human adaptation skills while opening new prospects for resilient healthcare performance. Hossain and Thakur [27] came up with the idea and built scales for measuring the performance of the smart healthcare supply chain. Using IBM SPSS AMOS 26 software, the study used structural equation modeling to examine survey results from 323 people. The authors suggested a holistic approach considering HCSC responsiveness and industry 4.0 technologies. However, the generalizability of the scales to first-world countries was limited, as they were validated from the perspective of developing countries like India.

According to the literature survey, past research has examined several aspects of Industry 4.0 and Healthcare 4.0 technologies in supply chain management. However, a gap exists in developing a comprehensive evaluation framework that integrates technical and economic criteria, particularly in developing countries. This study fills this gap by proposing a multi-criteria framework that synergistically combines techno-economic implications of Healthcare 4.0 technologies to improve healthcare supply chain management in a developing country. The framework utilizes fuzzy VIKOR and Entropy methods to handle data vagueness and uncertainty, which is a common challenge in assessing the impact of these technologies in resource-constrained settings.

3. Materials and Methods

3.1. Problem

The healthcare supply chain is a complex system comprising several players, processes, and technologies. Implementing Healthcare 4.0 technologies like the Internet of Things (IoT), artificial intelligence (AI), and blockchain could transform supply chain management in the healthcare industry. Assessing the influence of these technologies on the efficiency of healthcare supply chains is difficult, especially in developing nations. The primary challenge in evaluating the influence of Healthcare 4.0 technologies on healthcare supply chain management is the absence of in-depth evaluation frameworks that incorporate technical and economic aspects. Previous research has mainly concentrated on the technical features of these technologies, like their functionality and performance, without adequately addressing the economic implications, such as cost–benefit analysis and return on investment [10–12,23–25]. Another significant challenge is the vagueness and uncertainty inherent in data needed to assess Healthcare 4.0 technologies in supply chain management. Healthcare providers frequently encounter incomplete, imprecise, and subjective information, hindering conventional decision-making methods. Inaccurate data can impede the precise evaluation of how these technologies affect supply chain performance.

In addition, the healthcare supply chain management assessment of Healthcare 4.0 technologies must consider the unique challenges and barriers encountered by institutions in developing nations. The barriers include inadequate infrastructure, limited resources, and a dearth of competent personnel [28]. Adopting and implementing these technologies may also be impacted by developing countries' socioeconomic and cultural environments; therefore, a context-specific evaluation strategy is necessary. Addressing these issues is critical for developing-country healthcare organizations to make educated investment and adoption decisions for Healthcare 4.0 technology. Without a comprehensive knowledge of the technical and economic implications and an effective strategy for dealing with data ambiguity and uncertainty, these organizations may struggle to realize the full potential of these technologies in terms of enhancing supply chain performance and, ultimately, patient outcomes. Given the unique challenges that exist in developing countries, this research proposes a robust framework that can be utilized to assess the effects of Healthcare 4.0 technologies on the administration of healthcare supply chains.

By incorporating fuzzy VIKOR and Entropy techniques, the proposed framework will effectively manage issues related to vagueness and uncertainty in data, offering a more reliable and context-specific methodology for assessing Healthcare 4.0 technologies. The goal is to strategically apply the fuzzy entropy method to assess the techno-economic characteristics important for determining the relative importance of Industry 4.0 technologies. The impact of these technologies on the healthcare supply chain will then be measured using the fuzzy VIKOR approach. This decision-making problem aims to optimize healthcare supply chain management practices by offering a methodical approach that enables stakeholders to make well-informed decisions on integrating and applying Industry 4.0 technology.

3.2. Proposed Framework

The proposed framework for assessing the impact of Healthcare 4.0 technologies on healthcare supply chain management is illustrated in Figure 1. The framework comprises three primary components: Healthcare 4.0 technology, evaluation criteria, and the multi-criteria decision-making (MCDM) technique. It considered four areas of Healthcare 4.0 applications in the healthcare sector:

- Remote Diagnostics—Utilizing IoT and telemedicine for remote patient monitoring and diagnostics.
- Smart Inventory—Implementing RFID and automation for efficient inventory management of medical supplies.
- AI-assisted healthcare—Incorporating artificial intelligence for treatment decision support and predictive analytics.
- Blockchain Tracking—Implementing blockchain for transparent and secure traceability of pharmaceuticals and medical equipment.

The framework's evaluation criteria include factors related to both technical and economic considerations. The technical criteria analyze the feasibility, reliability, and performance of Healthcare 4.0 technologies, while the economic criteria assess the economic effect and sustainability of implementing these technologies. This framework utilizes the MCDM technique, which integrates fuzzy VIKOR and fuzzy entropy methods to address the ambiguity and unpredictability in the data provided by healthcare supply chain experts. The fuzzy VIKOR technique prioritizes Healthcare 4.0 technologies by assessing their performance against assessment criteria, considering decision-makers' preferences and criteria weights. The entropy approach calculates the criteria's objective weights, guaranteeing a balanced and unbiased evaluation.

The framework operates by first gathering information from healthcare supply chain specialists about the performance of Healthcare 4.0 technology against the evaluation criteria. This information is then evaluated using the fuzzy VIKOR and Entropy methods to rank the technologies and determine which are most suited for application in the healthcare supply chain. The framework's output offers decision-makers a ranked list of Healthcare 4.0 technologies and an analysis of their strengths and limitations based on evaluation criteria. This information would assist healthcare organizations in making well-informed decisions regarding adopting and implementing these technologies, considering their particular requirements, resources, and limitations.

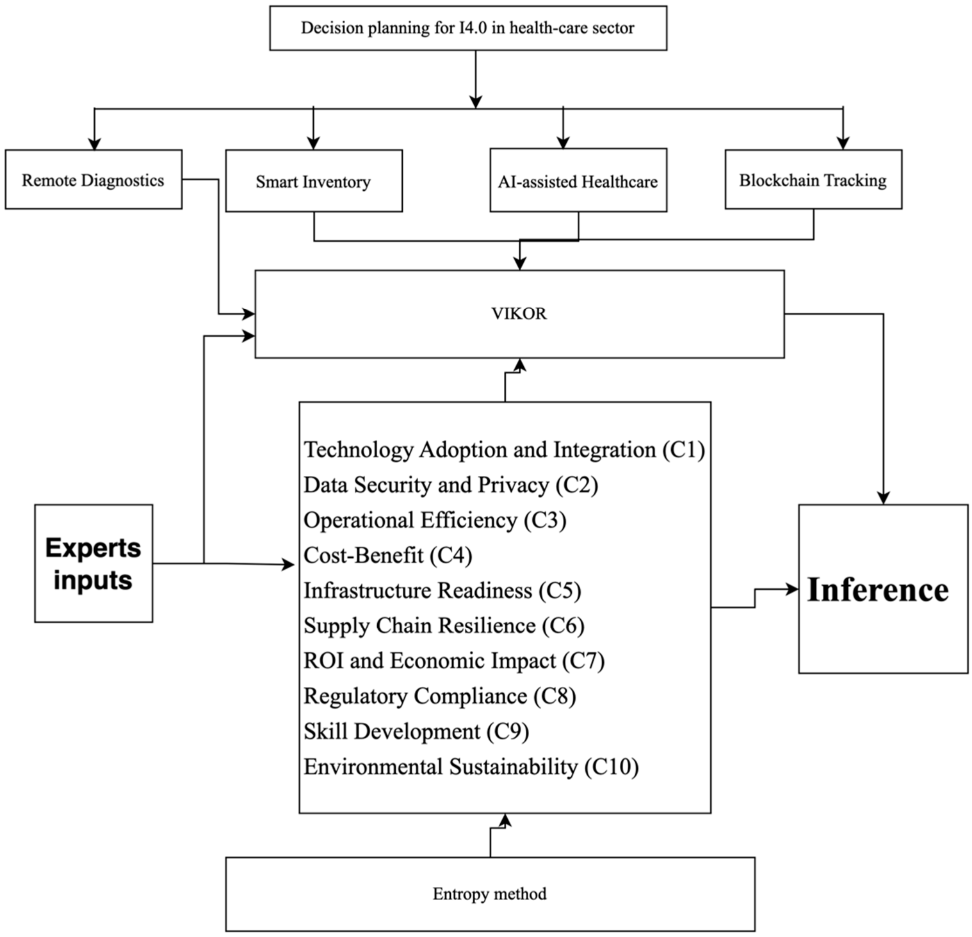

Figure 1. Framework for Healthcare 4.0 impact on health care supply chain.

By providing a comprehensive and context-specific approach to evaluating Healthcare 4.0 technologies, the proposed framework contributes to advancing knowledge and practice in healthcare supply chain management, particularly in developing countries. The framework helps bridge the gap between theory and practice, offering a practical tool for healthcare organizations to assess the impact of these technologies on their supply chain performance and make data-driven decisions to improve patient care and operational efficiency.

3.3. Selection of Evaluation Criteria

The evaluation criteria in the proposed framework were selected after a comprehensive analysis of the Healthcare 4.0 and supply chain management literature, along with input from healthcare experts and supply chain specialists. The criteria were selected to offer an in-depth assessment of the influence of Healthcare 4.0 technology on several facets of supply chain management in the healthcare industry.

The technical criteria, such as technology adoption and integration (C1), data security and privacy (C2), and infrastructure readiness (C5), were selected because they are critical to ensuring the successful implementation and operation of Healthcare 4.0 technologies [29]. These factors are crucial in determining the feasibility and effectiveness of implementing these technologies in healthcare supply chains. Economic parameters such as cost–benefit (C4), ROI and economic impact (C7), and operational efficiency (C3) were used to assess the financial viability and performance benefits of using Healthcare 4.0 technology [30]. These criteria are essential for justifying investments in these technologies and ensuring their long-term viability. Furthermore, criteria such as supply chain resilience (C6) [31], regulatory compliance (C8) [20], skill development (C9) [32], and environmental sustainability

(C10) [20] were incorporated to capture the broader impacts of Healthcare 4.0 technologies on the healthcare supply chain. The criteria emphasize the importance of a comprehensive evaluation strategy for assessing the effects of various technologies, considering technical, economic, social, and environmental factors.

The choice of these criteria was validated through discussions with experts such as healthcare administrators, supply chain managers, industrial engineers, and technology specialists. The experts gave feedback on the criteria's relevance and completeness, ensuring that they appropriately reflect the essential variables driving the success of Healthcare 4.0 technologies in supply chain management. The various criteria considered in this study are defined as follows:

1. Technology Adoption and Integration (C1): Assesses the extent to which the new technology is adopted and integrated into the existing healthcare supply chain infrastructure.
2. Data Security and Privacy (C2): Focuses on the security measures in place to protect sensitive patient and operational data within the implemented technologies.
3. Operational Efficiency (C3): Measures the degree to which the I4.0 solutions improve operational processes, streamline workflows, and reduce inefficiencies within the healthcare supply chain.
4. Cost–Benefit (C4): Evaluates the financial implications of implementing these technologies compared to the benefits they offer in terms of efficiency, cost savings, and improved healthcare delivery.
5. Infrastructure Readiness (C5): Assesses the existing infrastructure's readiness and compatibility to support the adoption of Industry 4.0 technologies.
6. Supply Chain Resilience (C6): Measures the ability of the new technologies to enhance the resilience of the healthcare supply chain, especially in addressing disruptions and ensuring continuity.
7. ROI and Economic Impact (C7): Examines the return on investment and overall economic impact resulting from the implementation of Industry 4.0 solutions in the healthcare supply chain.
8. Regulatory Compliance (C8): Assesses adherence to local and international regulations, ensuring that the implemented technologies comply with healthcare and data privacy laws.
9. Skill Development (C9): Evaluates efforts in upskilling or training the workforce to effectively use and manage the new technologies integrated into the healthcare supply chain.
10. Environmental Sustainability (C10): Focuses on the environmental impact of the Healthcare 4.0 technologies, assessing their contribution to sustainability and eco-friendly practices within the healthcare system.

3.4. MCDM

This subsection discusses the MCDM methods adopted in the study's implementation. The study adopts the fuzzy MCDM approach. The fuzzy approach was selected as the basis for the proposed MCDM framework because of its capability to manage the inherent ambiguity and vagueness in assessing the impact of Healthcare 4.0 technologies on supply chain management. Fuzzy reasoning enables the integration of human experience and judgment into decision-making, which is beneficial in healthcare due to the presence of qualitative aspects that are challenging to quantify [33]. Decision-makers in the healthcare industry encounter difficulties when evaluating the effects of new technology because of insufficient data accuracy and the intricate decision-making environment. Fuzzy logic allows for capturing and processing imprecise and subjective information through linguistic variables and fuzzy sets [34]. Decision-makers can provide ratings using common language phrases like "low", "medium", or "high", which are then transformed into fuzzy numbers for analysis [35,36].

The proposed framework utilizes a fuzzy set to provide a realistic and flexible representation of the decision-making process, capturing uncertainties and subjectivities while evaluating the influence of Healthcare 4.0 technologies on supply chain management. By incorporating fuzzy logic, the framework provides a robust and reliable approach to support healthcare decision-makers in making informed choices regarding adopting and implementing these technologies. Moreover, fuzzy logic is well-suited for handling the multi-criteria nature of the decision-making problem considered in this study. Evaluating Healthcare 4.0 technology requires assessing various factors that may conflict, including technological feasibility, economic viability, and social effect [37]. Fuzzy Multi-Criteria Decision Making (MCDM) techniques, including fuzzy AHP, fuzzy TOPSIS, and fuzzy VIKOR, are commonly employed in research to tackle comparable decision-making issues across different fields, including healthcare [38–41].

3.4.1. Fuzzy Entropy Method

This method has been used to generate empirical information about the diverse criteria in decision science. Its capacity to seamlessly analyze linguistic data is among many of its applicability. This method simplified criteria evaluation using four steps that are not only easy to understand but also easy to implement. However, its fuzzy version requires more steps because of the need to convert linguistic variables to crisp values.

Technically, fuzzy arithmetic operations are carried out before implementing this method (Equations (1)–(3)). Given two fuzzy set, $x = a_1, b_1, c_1$ and $y = a_2, b_2, c_2$, an addition operation of these sets is expressed as Equation (1).

$$x + y = a_1 + a_2, b_1 + b_2, c_1 + c_2, \tag{1}$$

Similarly, the multiplication operation for these sets is expressed as Equation (2)

$$xy = a_1a_2, b_1b_2, c_1c_2, \tag{2}$$

Lastly, the scalar multiplication (k) is also applicable to fuzzy arithmetic (Equation (3)).

$$kx = ka_1, kb_1, kc_1 \tag{3}$$

Equations (1)–(3) are specific to the linguistic values expressed as triangular fuzzy numbers. It is important to note there are other types of fuzzy numbers, such as trapezoidal fuzzy numbers. For triangular fuzzy numbers, Equation (4) gives the expression of the crisp values [42].

$$x_i = \frac{a_{1i} + 4b_{1i} + c_{1i}}{6} \tag{4}$$

With the crisp values of a decision matrix's criteria (Equation (5)), the entropy method can be applied as follows:

$$D = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \tag{5}$$

The values in this matrix are normalized to initiate an entropy method implementation (Equation (6)).

$$p_{ij} = \frac{x_{ij}}{\sum_j x_{ij}} \tag{6}$$

The normalized values are further processed to generate the criteria entropy measures, Equation (7).

$$e_j = -k\sum_{j=1}^{n} p_{ij} ln(p_{ij}) \tag{7}$$

where $k = \frac{1}{ln(m)}$.

These measures are used to determine the criteria divergence, Equation (8).

$$div_j = 1 - e_j \tag{8}$$

Lastly, the divergence values are normalized to generate a criterion significance for a decision-making problem, Equation (9).

$$w_j = \frac{div_j}{\sum_j div_j} \tag{9}$$

3.4.2. Fuzzy VIKOR Method

The VIKOR method is a robust decision-making tool because it considers the best and worst values for criteria and alternatives to generate information about the suitability of alternatives for a problem. This method uses the relationship between criteria and alternatives to supply information about the suitability of alternatives for a decision-making problem. Hence, its implementation is governed by the information in a decision matrix. This implies that the suitability of an alternative is a function of its impacts and criteria significance for a decision-making problem [43].

To implement a VIKOR method, utility values are generated for the alternatives to a decision-making problem (Equation (10)). This process involves identifying the best solutions for criteria in a decision matrix (Equation (11)). Similarly, consideration is given to the worst solutions for the criteria in the decision matrix (Equation (12)).

$$S_i = \sum_{j=1}^{n} \frac{w_j\left(f_i^* - f_{ij}\right)}{f_i^* - f_i^-} \tag{10}$$

$$f_i^* = \max_i f_{ij} \tag{11}$$

$$f_i^- = \min_i f_{ij} \tag{12}$$

The relationship between the best solutions, criteria weights, and the worst solutions is used to generate the alternatives' regret values (Equation (13)).

$$R_i = \max_i \left(\frac{w_j\left(f_i^* - f_{ij}\right)}{f_i^* - f_i^-} \right) \tag{13}$$

Using the utility and regret values, the alternatives' VIKOR values are determined (14). The values depend on the utility ideal and non-ideal solutions among the alternatives (Equations (15) and (16)). Furthermore, emphasis is given to the ideal and non-ideal solutions among the alternatives' regret values (Equations (17) and (18)).

$$Q_i = \nu \frac{S_i - S^*}{S^- - S^*} + (1 - \nu) \frac{R_i - R^*}{R^- - R^*} \tag{14}$$

$$S^- = \max_i S_i \tag{15}$$

$$S^* = \min_i S_i \tag{16}$$

$$R^* = \max_i R_i \tag{17}$$

$$R^- = \min_i S_i \tag{18}$$

The alternatives are ranked based on a lower-the-best basis [43]. The conditions for ensuring optimality during a decision-making process are presented by Ighravwe et al., 2022 [43].

3.4.3. TOPSIS Method

This method has established itself as a major MCDM method in decision science. This is evident in its appearance in several publications [44–46]. Its attractiveness to researchers and scholars is because it uses the ideal and non-ideal solutions to establish an alternative's appropriateness for a decision-making problem. Technically, this method is implemented as follows:

Matrix formation

This entails identifying the alternatives for a decision-making problem and appropriate criteria for evaluating the suitability of alternatives for the problem.

Data collection

This entails using a questionnaire or operational or experimental data to collect relevant information for this method implementation. For example, this study uses a questionnaire to collect information from experts about the technology's suitability (Appendix A).

Determine the criteria importance

From the collected data, the importance of the criteria is determined. This study used the entropy method to determine the importance of the criteria. For example, see the previous discussion on the fuzzy entropy method for more details.

Determine the alternatives' suitability

The suitability of alternatives is determined using a weighted normalized decision matrix. The matrix contains information about the evaluation criteria and the impact of alternatives on each criteria. The normalized values are generated using criteria orientation, which is cost- or benefit-oriented. Equation (19) presents the expression used to normalized the alternative values, while Equation (20) presents the decision matrix for the weighted normalized matrix.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n}\left(x_{ij}\right)^2}} \tag{19}$$

$$D_w = \begin{bmatrix} w_1 r_{11} & \cdots & w_n r_{1n} \\ \vdots & \ddots & \vdots \\ w_1 r_{m1} & \cdots & w_n r_{mn} \end{bmatrix} \tag{20}$$

The information in the weighted normalized matrix is used for the ideal and non-ideal solutions, as shown in Equations (21) and (22), respectively.

$$d_j^+ = \begin{cases} \max_i x_{ij}\ for\ benefit - oriented\ criteria \\ \min_i x_{ij}\ for\ cost - oriented\ criteria \end{cases} \tag{21}$$

$$d_j^+ = \begin{cases} \max_i x_{ij}\ for\ cost - oriented\ criteria \\ \min_i x_{ij}\ for\ benefit - oriented\ criteria \end{cases} \tag{22}$$

These ideal and non-ideal solutions are used to determine the alternatives' ideal distance (23) and their non-ideal distance (24).

$$d_j^+ = \sqrt{\left(n_{ij} - n_j^+\right)^2} \tag{23}$$

$$d_j^- = \sqrt{\left(n_{ij} - n_j^-\right)^2} \tag{24}$$

Based on these distances, the alternatives' closeness co-efficiencies are determined (Equation (25)).

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{25}$$

4. Case Study

The research paper presents a case study that assesses the effects of Healthcare 4.0 technologies on the management of healthcare supply chains in Nigeria. The research paper presents a case study that assesses the effects of Healthcare 4.0 technologies on managing healthcare supply chains in Nigeria. Nigeria, a developing nation, offers a distinct environment for studying the implementation and effects of these technologies because of its specific challenges, inadequate infrastructure, limited resources, and a shortage of skilled workers [47–49]. Second, Nigeria has been making significant efforts to adopt and implement various Healthcare 4.0 technologies to improve the performance of its healthcare system [50]. Examining the impact of these technologies on supply chain management in Nigeria can provide valuable insights for other developing countries facing similar challenges.

This study made use of a questionnaire to gather data from experts (E1, E2, and E3) with an in-depth understanding of Healthcare 4.0 and skillful application of Multi-Criteria Decision Making (MCDM) techniques in the healthcare industry. The selection of these experts was based on their proven skill at using cutting-edge strategies to address the complexity of healthcare systems.

The questionnaire has two sections. The purpose of the first section was to use Table 1's information to get information from the experts. This section made it easier to evaluate the techno-economic criteria that are essential for determining how Healthcare 4.0 technologies would affect the management of the healthcare supply chain. The data obtained from the questionnaires and literature review was evaluated using the fuzzy VIKOR and Entropy methods outlined in the proposed framework. The results of the analysis and insights from the case study will be presented in the results and discussion section.

Table 1. Linguistic rating for the criteria importance.

Rating	TFN
Extremely important	(0.1, 0.2, 0.3)
Very important	(0.2, 0.3, 0.4)
Important	(0.3, 0.4, 0.5)
Moderately important	(0.4, 0.5, 0.6)
Indecisive	(0.5, 0.6, 0.7)
Unimportant	(0.6, 0.7, 0.8)
Highly unimportant	(0.7, 0.8, 0.9)
Extremely unimportant	(0.8, 0.9, 1.0)

The second part of the questionnaire probed more deeply into the subtleties of Healthcare 4.0, examining the complex interplay between techno-economic criteria and technologies. Experts were asked to offer critical evaluations in this area, evaluating the Healthcare 4.0 technologies in the healthcare supply chain. The experts used the information in Table 2 to evaluate the suitability of the technologies in a developed country's healthcare system.

The attributions of the three experts are presented as follows:

- E1 has over 15 years of expertise in optimizing healthcare supply chains and holds a Ph.D. in healthcare logistics. Has written a great deal about applying technological innovations to healthcare logistics. She is well known for developing the first approaches to incorporate Industry 4.0 technologies into healthcare supply chains, resulting in increased efficacy and economy.
- E2 has two degrees: one in medicine and one in data science. Has ten years of experience using data analytics to enhance hospital operations. Renowned for creating

algorithms that maximize medical resource utilization. His specialty is the analysis and interpretation of huge datasets to derive significant insights for well-informed healthcare decision-making.

- E3 holds an MBA with a concentration in technology management. She has made significant contributions to the introduction and use of innovative technology in the developing world's healthcare system. She is renowned for her ability to create and carry out technology adoption strategies that are especially suited for healthcare systems operating in resource-constrained settings.

Table 2. Linguistic rating for the technology's impacts.

Rating	TFN
Extremely high (EH)	(0.1, 0.2, 0.3)
Very high (VH)	(0.2, 0.3, 0.4)
High (H)	(0.3, 0.4, 0.5)
Moderate (M)	(0.4, 0.5, 0.6)
Indecisive (I)	(0.5, 0.6, 0.7)
Low (L)	(0.6, 0.7, 0.8)
Highly low (HL)	(0.7, 0.8, 0.9)
Extremely low (EL)	(0.8, 0.9, 1.0)

Table 3 presents the linguistic evaluation of the criteria used for the framework's implementation.

Table 3. Experts' evaluation of the criteria.

Criteria	E1	E2	E3
Technology adoption and integration	EI	H	EI
Data security and privacy	EI	VL	EI
Operational efficiency	EI	L	I
Cost–benefit	VI	M	VI
Infrastructure readiness	VI	VL	VI
Supply chain resilience	I	M	MI
ROI and economic impact	I	H	VI
Regulatory compliance	I	L	EI
Skill development	I	L	EI
Environmental sustainability	VI	L	VI

Table 4 presents the linguistic evaluation of the technologies used for the framework's implementation while the Aggregate values of the criteria is presented in Table 5.

Table 4. Experts' evaluation of the Healthcare 4.0 technology.

Criteria	Remote Diagnostics	Smart Inventory	AI-Assisted Healthcare	Blockchain Tracking
Technology adoption and integration	VH, H, EH	VH, L, EH	VH, VL, EH	H, L, EH
Data security and privacy	VH, VL, EH	VH, L, EH	H, VL, EH	H, L, EH
Operational efficiency	VH, L, H	VH, L, EH	H, L, EH	H, L, EH
Cost–benefit	H, M, M	VH, H, H	VH, VH, H	VH, VH, EH
Infrastructure readiness	VH, VL, H	H, VL, VH	VH, L, H	VH, L, VH
Supply chain resilience	VH, M, H	H, M, H	H, L, H	H, L, EH
ROI and economic impact	VH, H, H	VH, VH, M	VH, VH, H	VH, VH, VH
Regulatory compliance	H, L, H	VH, M, M	H, L, VH	VH, L, M
Skill development	H, L, VH	H, L, H	VH, L, VH	VH, L, H
Environmental sustainability	H, L, EH	H, L, M	VH, L, VH	H, L, H

Table 5. Aggregate values of the criteria.

Criterion	*l*	*m*	*u*
Technology adoption and integration	0.600	0.833	1.000
Data security and privacy	0.700	0.867	1.000
Operational efficiency	0.300	0.667	1.000
Cost–benefit	0.500	0.733	0.900
Infrastructure readiness	0.700	0.800	0.900
Supply chain resilience	0.500	0.633	0.800
ROI and economic impact	0.600	0.733	0.900
Regulatory compliance	0.300	0.667	1.000
Skill development	0.300	0.667	1.000
Environmental sustainability	0.300	0.667	0.900

5. Results and Discussion

The criteria importance for Healthcare 4.0 technology evaluation is presented in Figure 2 and the aggregated values are presented in Table 6. Operational efficiency was considered the most significant criterion for selecting suitable Healthcare 4.0 technology implementation in the case study. In healthcare systems, it offers improved patient care because it reduces wait times, enhances access to healthcare, and optimizes healthcare resource allocation. From a staff perspective, it boosts staff productivity and compliance.

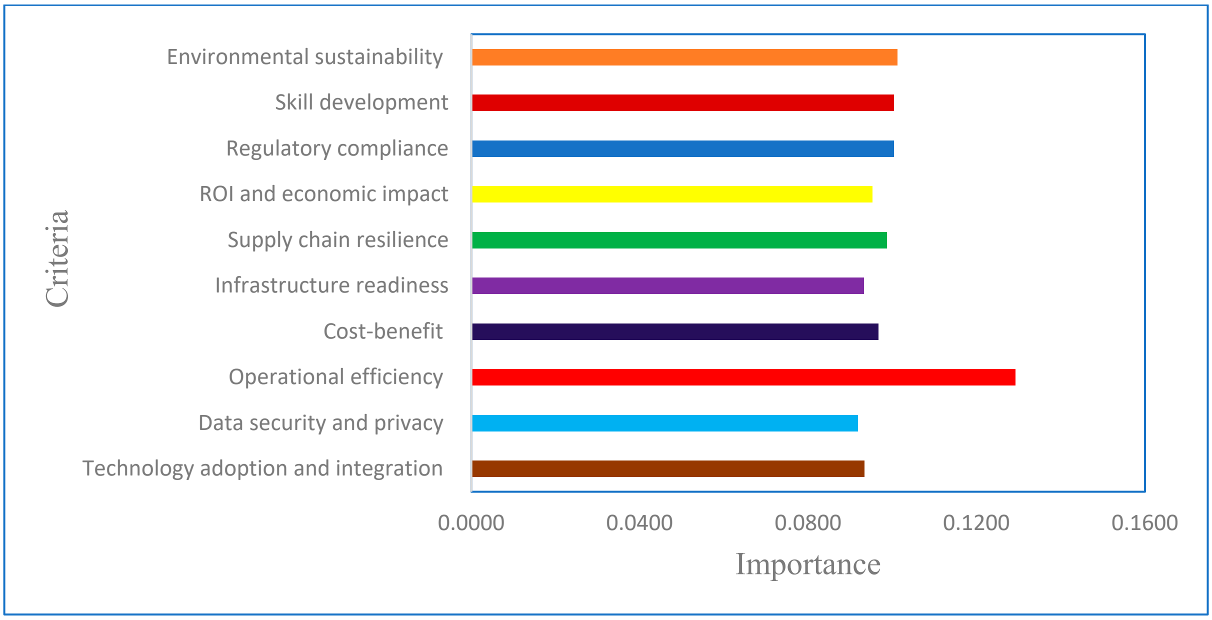

Figure 2. Criteria importance for Healthcare 4.0 technology evaluation.

This study used a contribution factor of 0.5 [51] to combine the technologies measures in Table 7. The resulting VIKOR index from this combination is presented in Figure 3. Among the Healthcare 4.0 technologies, we observed that remote diagnostics technology was the most significant technology in the study area. This result showed that people seeking healthcare services are ready to embrace remote diagnosis because of its impact on the stated criteria. AI-assisted healthcare technology was ranked second among the stated technologies. This technology has the potential to improve the benefits that could be derived from remote diagnosis among healthcare seekers and medical practitioners. The performance of the technologies based on utility and regret is shown in Table 8.

Table 6. Aggregate values the technologies.

	l				*m*			
	T1	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**
Technology adoption and integration	6.000	3.000	2.000	3.000	8.000	7.000	6.667	6.667
Data security and privacy	2.000	3.000	2.000	3.000	6.667	7.000	6.333	6.667
Operational efficiency	3.000	3.000	3.000	3.000	6.333	7.000	6.667	6.667
Cost–benefit	5.000	6.000	6.000	7.000	6.333	7.333	7.667	8.333
Infrastructure readiness	2.000	2.000	3.000	3.000	6.000	6.000	6.333	6.667
Supply chain resilience	5.000	5.000	3.000	3.000	7.000	6.667	6.000	6.667
ROI and economic impact	6.000	5.000	6.000	7.000	7.333	7.333	7.667	8.000
Regulatory compliance	3.000	5.000	3.000	3.000	6.000	6.667	6.333	6.000
Skill development	3.000	3.000	3.000	3.000	6.333	6.000	6.667	6.333
Environmental sustainability	3.000	3.000	3.000	3.000	6.667	5.667	6.667	6.000
	u							
Technology adoption and integration	10.000	10.000	10.000	10.000				
Data security and privacy	10.000	10.000	10.000	10.000				
Operational efficiency	9.000	10.000	10.000	10.000				
Cost–benefit	8.000	9.000	9.000	10.000				
Infrastructure readiness	9.000	9.000	9.000	9.000				
Supply chain resilience	9.000	8.000	8.000	10.000				
ROI and economic impact	9.000	9.000	9.000	9.000				
Regulatory compliance	8.000	9.000	9.000	9.000				
Skill development	9.000	8.000	9.000	9.000				
Environmental sustainability	10.000	8.000	9.000	8.000				

Table 7. Weighted values of the technologies.

Criterion	Remote Diagnostics	Smart Inventory	AI-Assisted Healthcare	Blockchain Tracking
Technology adoption and integration	0.028	0.023	0.021	0.022
Data security and privacy	0.022	0.024	0.021	0.024
Operational efficiency	0.031	0.034	0.032	0.032
Cost–benefit	0.021	0.024	0.025	0.027
Infrastructure readiness	0.022	0.022	0.024	0.025
Supply chain resilience	0.027	0.026	0.022	0.024
ROI and economic impact	0.023	0.023	0.024	0.025
Regulatory compliance	0.023	0.028	0.025	0.024
Skill development	0.025	0.024	0.026	0.025
Environmental sustainability	0.027	0.023	0.027	0.024

Table 8. Performance of the technologies.

Measure	Remote Diagnostics	Smart Inventory	AI-Assisted Healthcare	Blockchain Tracking
Utility	0.398	0.462	0.000	1.000
Regret	0.000	1.000	0.602	0.602

Smart inventory technology in healthcare systems was ranked as the third technology among the stated Healthcare 4.0 technologies. In implementing remote diagnostics technology, healthcare service providers need to consider this technology because it will help to reduce the lead time between requests and delivery of prescriptions for clients. Lastly, we observed that blockchain tracking was ranked as the fourth technology. This technology needs to be upgraded for its impact to be effective among stakeholders in healthcare systems.

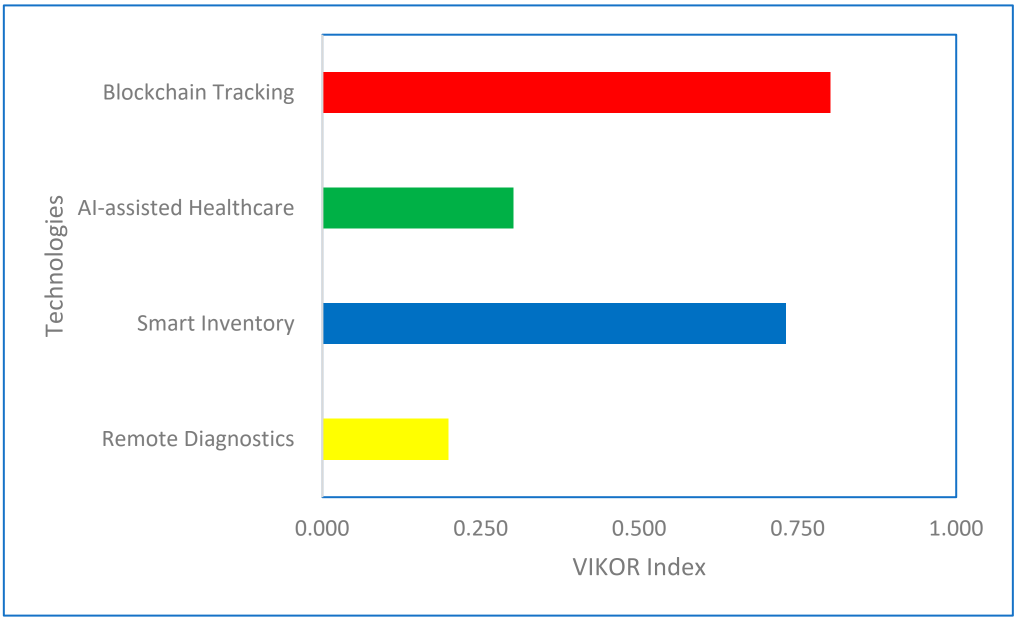

Figure 3. F-VIKOR for the technologies.

Using the information in Table 7, this study implemented the TOPSIS method discussed above. The ideal and non-ideal distances from solutions for the technologies is given in Table 9.

Table 9. Technologies distances from the solutions.

Measure	Remote Diagnostics	Smart Inventory	AI-Assisted Healthcare	Blockchain Tracking
Ideal	0.010	0.009	0.011	0.009
Non-ideal	0.010	0.008	0.007	0.009

Figure 4 presents the technologies' closeness co-efficiencies for the decision-making problem.

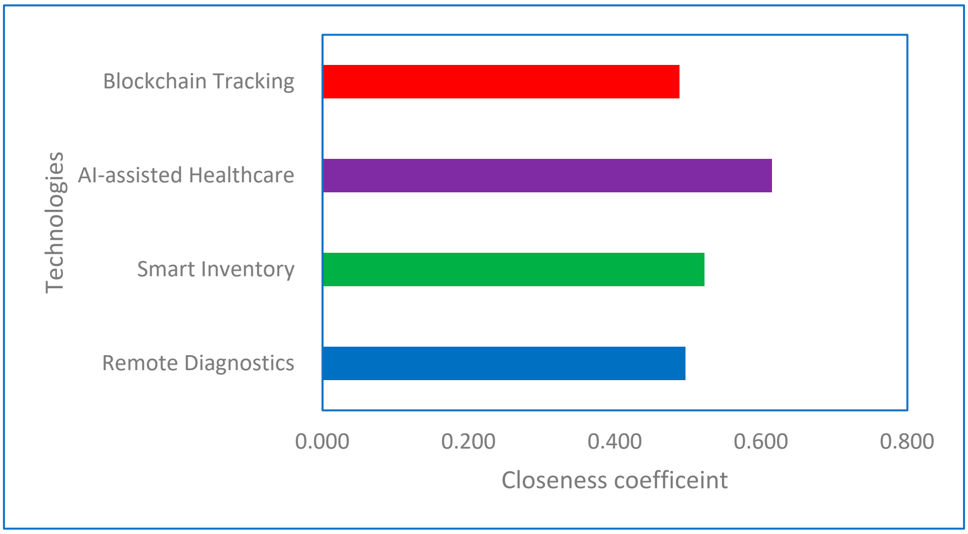

Figure 4. Technologies closeness co-efficiencies.

The results of the TOPSIS analysis showed that the best technology was AI-assisted healthcare. This result deviates from the results of the VIKOR method, which demonstrates the influence of their different approaches. Whereas the VIKOR method focused on a single perfect answer, the TOPSIS approach considered several ideal solutions. Figure 4 shows that the technology that was least appropriate for the case study was blockchain tracking technology; Figure 3 also shows that blockchain tracking was the least suitable technology. Furthermore, smart inventory was found to be the next most appropriate technology by the TOPSIS results, with remote diagnostic technology for healthcare systems coming in third.

This study used Equation (26) to combine the VIKOR and TOPSIS results. This equation integrates the ranking scores from Fuzzy VIKOR and Fuzzy TOPSIS by calculating the reciprocal of the sum of the reciprocals of the individual ranking scores. The inverse of the ranking scores is used to ensure that a lower (better) ranking score in either method contributes more to the final ranking score. By summing the reciprocals of the individual ranking scores, this approach gives equal weight to both methods and provides a balanced combination of their results. Combining the results from both methodologies gives a more comprehensive evaluation of the applicability of the various Healthcare 4.0 technologies for the case study. The combined results account for the strengths of both methodologies and provide a fair assessment of the technologies' performance across numerous evaluation criteria.

The results obtained showed that AI-assisted Healthcare was the most suitable technology for the case study. It was also observed that the blockchain tracking technology was the least suitable technology, while smart inventory ranking was slightly preferred to the blockchain tracking technology. Remote diagnostic technology was ranked as the second preferred technology.

$$R_i^f = \frac{1}{1/R_i^{VIKOR} + 1/R_i^{TOPSIS}} \tag{26}$$

5.1. Sensitivity Analysis

The robustness of the proposed framework was evaluated by changing the contribution factor for the VIKOR method. Figure 4 shows the sensitivity analysis results for the technologies for nine runs. Using ANOVA, we observed that there was no significant difference in the results presented in Figure 5 at a significant level of 10% (Table 10). These results were used to generate the ranking in Table 11. These rankings showed that there were slight changes in the technologies ranking.

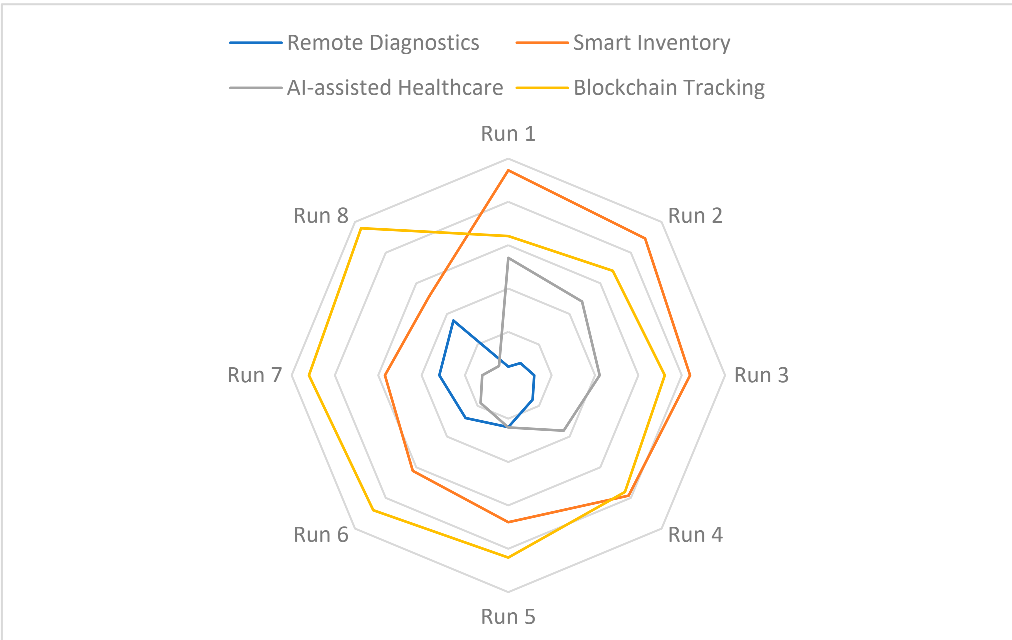

Figure 5. Sensitivity analysis results for the technologies.

Table 10. ANOVA results for the Healthcare 4.0 technologies analysis.

Source of Variation	SS	df	MS	F	*p*-Value	F Crit
Rows	0.018	7	0.003	0.095	0.998	2.488
Columns	2.192	3	0.731	27.227	0.000	3.072
Error	0.563	21	0.027			
Total	2.773	31				

Table 11. Healthcare 4.0 technologies ranking.

Run	Remote Diagnostics	Smart Inventory	AI-Assisted Healthcare	Blockchain Tracking
1	1	4	2	4
2	1	4	2	3
3	1	4	2	3
4	1	4	2	3
5	1	3	2	4
6	2	3	1	4
7	2	3	1	4
8	2	3	1	4

On the one hand, we observed that remote diagnostics was ranked first out of the eight runs. On the other hand, smart inventory and blockchain tracking were ranked fourth in the runs presented in Figure 4. Hence, it could be deduced that remote diagnostics technology is the most significant Healthcare 4.0 technology for the case study. This shows that the proposed framework is reliable for evaluating the significance of Healthcare 4.0 technology in healthcare systems.

5.2. Comparison with Previous Studies

The findings of this study reinforce and extend earlier studies on the impact of Healthcare 4.0 technology on supply chain management. Hossain and Thakur [17] identified HC logistics management as the highest priority for implementing Industry 4.0 in the healthcare supply chain during health outbreaks, which is consistent with our findings that operational efficiency is one of the most important criteria for evaluating Healthcare 4.0 technologies. This suggests that improving operational efficiency is crucial for implementing these technologies in healthcare supply chains. Similarly, Chatterjee et al. [18] stressed the importance of environmental dynamism in determining the relationship between Industry 4.0 technology adoption and healthcare supply chain management. This study's evaluation framework considers technical and economic criteria, emphasizing the necessity of context-specific elements in assessing these technologies.

Additionally, this study's analysis of the suitability of various Healthcare 4.0 technologies—such as AI-assisted healthcare, remote diagnostic technology, and smart inventory management—for supply chain management in the healthcare industry complements the results of earlier research. For instance, Luz et al. [10] used case studies from Brazil and India (both developing countries) to provide insights for healthcare companies in prioritizing their digitization efforts, whereas AbdelMouty et al. [19] validated the efficacy of a framework for examining the impact of IoT and Industry 4.0 on healthcare supply chain operations. While our study did not specifically examine the influence of blockchain technology on healthcare supply chain management, our findings align with the research conducted by Vishwakarma et al. [24]. They observed that blockchain technology positively impacts healthcare supply chain practices and performance. Blockchain technology and other Healthcare 4.0 technologies can potentially enhance supply chain operations in the healthcare industry.

5.3. Managerial Implications

This study's findings have important implications for managers and decision-makers in healthcare supply chain management, especially in developing nations such as Nigeria. The proposed approach and the knowledge acquired from the case study can assist managers in making well-informed decisions regarding the adoption and integration of Healthcare 4.0 technologies to enhance supply chain performance.

The study emphasizes the importance of operational efficiency, data security and privacy, and technological adoption and integration when assessing the effects of Healthcare 4.0 technologies on healthcare supply chain management. Managers should give importance to these factors when deciding to implement these technologies and ensure that the chosen technologies align with their organization's objectives and capacities. This information can assist managers in efficiently allocating resources and devising specific strategies for technology deployment. The case study indicates that remote diagnostics, AI-assisted healthcare, and smart inventory management are the most relevant Healthcare 4.0 technologies for enhancing supply chain management in Nigeria. Managers can utilize this information to implement these technologies and achieve their potential benefits, including cost reduction, more significant patient outcomes, and improved operational efficiency. By prioritizing these technologies, managers may optimize their investments and have a maximum impact on supply chain performance.

Furthermore, the study underlines the significance of considering the specific challenges and constraints faced by healthcare organizations in developing countries, such as limited infrastructure, scarce resources, and a lack of skilled personnel. Managers should evaluate their organization's readiness to implement Healthcare 4.0 technologies and devise plans to bridge any gaps or hurdles. This could include investments in capacity building, infrastructure development, and collaboration with technology suppliers and other stakeholders. In addition, the proposed framework offers managers a valuable tool for assessing the influence of Healthcare 4.0 technologies on their organization's supply chain performance. Managers can use the framework, built on fuzzy VIKOR and Entropy methodologies, to make data-driven decisions and prioritize technology investments based on their specific requirements and constraints. This can assist managers in maximizing resource allocation, reducing risks, and ensuring the long-term viability of their technology adoption activities.

Finally, the study emphasizes the ability of Healthcare 4.0 technology to revolutionize healthcare supply chain management and improve patient care in developing countries. Managers should recognize this potential and actively seek opportunities to adopt these technologies to boost their organization's competitiveness while contributing to the healthcare system's broader development. This could entail working with other stakeholders, such as government agencies, technology providers, and healthcare experts, to foster technology adoption and innovation.

6. Conclusions and Future Directions

6.1. Conclusions

Healthcare 4.0 has unquestionably transformed the healthcare industry's supply chain management by efficiently optimizing key resources like labor, equipment, supplies, and energy. Notwithstanding the apparent advantages, one significant obstacle continues to be the lack of approaches to thoroughly assess how Healthcare 4.0 components affect operational effectiveness. This study presented a framework that can be used to assess different Healthcare 4.0 technologies in the healthcare industry. The framework used a multi-criteria approach that incorporates the techno-economic criteria to evaluate Healthcare 4.0 technologies, especially when considering the healthcare supply chain of a developed nation. It successfully handled data vagueness and uncertainty faced during data collecting from three healthcare supply chain professionals in Lagos, Nigeria, by utilizing the unique characteristics of the fuzzy VIKOR and Entropy approaches.

The framework's results have identified which techno-economic criteria are the most and least important for adopting Healthcare 4.0 in the management of the Healthcare supply chain. Additionally, the study evaluated how well various Healthcare 4.0 technologies fit into the supply chain management framework used by the healthcare industry. The combination of these results provides a strong basis for encouraging the prudent implementation and assimilation of Healthcare 4.0 technologies, especially in the context of developed nation healthcare systems. The study focused on three primary research questions concerning the assessment of Healthcare 4.0 technologies in healthcare supply chain management. According to our research, the following were observed:

- The key technical and economic factors for assessing the influence of Healthcare 4.0 technologies on healthcare supply chain management in developing nations are operational efficiency (C3), data security and privacy (C2), and technology adoption and integration (C1). These characteristics emphasize the significance of evaluating both the technical viability and operational implications of these technologies within the unique setting of developing nations.
- This study identified remote diagnostics, AI-assisted healthcare, and smart inventory management as the most suitable Healthcare 4.0 technologies for enhancing supply chain management in the healthcare industry. These technologies provide the possibility of boosting operational efficiency, cutting expenses, and enhancing patient outcomes, making them appealing alternatives for healthcare organizations in developing nations.
- The proposed framework enhances knowledge and practice in implementing Healthcare 4.0 technologies in healthcare supply chains by offering an in-depth and context-specific method for assessing these technologies. The framework presents an innovative method of assessing technology by considering technical and economic factors, offering useful guidance for decision-makers. This study aids in bridging the gap between theory and practice in the rapidly emerging field of Healthcare 4.0 by advocating the appropriate implementation of technologies, especially in developing countries.

For academics, the proposed framework and evaluation criteria provide a foundation for further research on the impact of Healthcare 4.0 technologies in different contexts and settings. The study also highlights the need for more interdisciplinary research that combines technical and non-technical perspectives to develop a holistic understanding of technology adoption in healthcare supply chains.

6.2. Future Research Directions

While this study contributes significantly to the understanding of Healthcare 4.0 technologies and their impact on supply chain management, various areas for future research could expand on the findings of this study to address the limitations of this study. This study's consideration of techno-economic criteria is a limitation. This issue could be addressed by incorporating socio-environmental and institutional criteria into the proposed framework. Also, there is a need to include the experts' importance in implementing the framework; this issue could be considered for further study. Future research could investigate the application of the proposed framework in various geographic and institutional contexts to evaluate the generalizability of this study's findings and uncover context-specific factors impacting the uptake and effect of Healthcare 4.0 technology. Researchers could also investigate the long-term implications and unintended consequences of implementing these technologies, such as employment displacement, skill needs, and ethical concerns.

Additional data sources and methods, such as objective performance measurements, cost–benefit analyses, or simulation models, could supplement the expert opinions and fuzzy MCDM approach employed in this study. Furthermore, examining the role of organizational and human variables in the effective adoption of Healthcare 4.0 technologies, such as change management processes, leadership support, and staff training and engagement, could yield valuable insights. Finally, future research may examine the potential synergies and trade-offs between different Healthcare 4.0 technologies and their impact on supply chain performance to see how combining diverse technologies could result in larger efficiency benefits.

Addressing these future research directions will allow scholars to expand their understanding of the impact of Industry 4.0 on healthcare supply chain management, as well as advise practice and policy in this quickly evolving industry.

Author Contributions: Conceptualization, O.M.B. and A.O.; methodology, O.M.B.; software, O.M.B.; validation, O.M.B., O.A.O. and B.D.A.; formal analysis, O.M.B.; investigation, O.M.B. and A.O.; resources, O.M.B.; data curation, O.M.B.; writing—original draft preparation, O.M.B. and A.O.; writing—review and editing, O.M.B., A.O. and B.D.A.; supervision, O.A.O.; project administration, B.D.A.; funding acquisition, O.A.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Dataset available on request from the authors.

Acknowledgments: During the revision stage, the authors used AI for articulating the ideas from the literature and for grammar checks.

Conflicts of Interest: Author Ayoninuoluwa Oluwadare was employed by the company Aetna Inc., 151 Farmington Avenue. The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A. Sample of Questionnaire

Dear Expert,

We are conducting research on the impact of Industry 4.0 in revolutionizing the healthcare supply chain landscape, and your expertise is crucial in this endeavor. Hence, we invite you to take part in our questionnaire aimed at understanding the integration of Industry 4.0 technologies within the healthcare supply chain.

Please take a few moments to complete the questionnaire below by clicking on the boxes. Should you have any queries or require further information, please feel free to reach out to us. Thank you for being an integral part of this crucial evaluation.

XX

Criteria	Criteria	Remote Diagnostics	Smart Inventory	AI-Assisted Healthcare	Blockchain Tracking
Technology Adoption and Integration	Select importance level	Select impact level	Select impact level	Select impact level	Select impact level
Data Security and Privacy	Select importance level	Select impact level	Select impact level	Select impact level	Select impact level
Operational Efficiency	Select importance level	Select impact level	Select impact level	Select impact level	Select impact level
Cost–Benefit	Select importance level	Select impact level	Select impact level	Select impact level	Select impact level
Infrastructure Readiness	Select importance level	Select impact level	Select impact level	Select impact level	Select impact level
Supply Chain Resilience	Select importance level	Select impact level	Select impact level	Select impact level	Select impact level
ROI and Economic Impact	Select importance level	Select impact level	Select impact level	Select impact level	Select impact level
Regulatory Compliance	Select importance level	Select impact level	Select impact level	Select impact level	Select impact level
Skill Development	Select importance level	Select impact level	Select impact level	Select impact level	Select impact level
Environmental Sustainability	Select importance level	Select impact level	Select impact level	Select impact level	Select impact level

References

1. Porter, M.E.; Teisberg, E.O. *Redefining Health Care: Creating Value-Based Competition on Result*; Harvard Business Press: Boson, MA, USA, 2006.
2. Stalk, G., Jr.; Hout, T.M. Competing Against Time: How Time-Based Competition Is Reshaping Global Markets. Doctoral Dissertation, Doshisha University, Kyoto, Japan, 1990.
3. Escoto, X.; Gebrehewot, D.; Morris, K.C. Refocusing the barriers to sustainability for small and medium-sized manufacturers. *J. Clean. Prod.* **2022**, *338*, 130589. [CrossRef]
4. Thuemmler, C. *The case for health 4.0. Health 4.0: How Virtualization and Big Data Are Revolutionizing Healthcare*; Springer: Berlin, Germany, 2017; pp. 1–22.
5. del Carmen Becerra, M.; Aballay, A.; Romagnano, M. Reflections on Healthcare Document Management in the Age of 4.0 Technologies. *Data Metadata* **2023**, *2*, 52. [CrossRef]
6. Swain, S.; Oyekola, P.O.; Muduli, K. Intelligent Technologies for Excellency in Sustainable Operational Performance in the Healthcare Sector. *Int. J. Soc. Ecol. Sustain. Dev. (IJSESD)* **2022**, *13*, 16. [CrossRef]
7. Vyas, S.; Bhargava, D.; Khan, S. Healthcare 4.0: A Systematic Review and Its Impact Over Conventional Healthcare System. In *Artificial Intelligence for Health 4.0: Challenges and Applications*; River Publisher: Aalborg, Denmark, 2023; pp. 1–17.
8. Bai, L.; Meredith, R.; Burstein, F. A data quality framework, method and tools for managing data quality in a health care setting: An action case study. *J. Decis. Syst.* **2018**, *27*, 144–154. [CrossRef]
9. de Siqueira Correa, E.; Sátyro, W.C.; da Silva, L.F.; Martens, M.L.; Contador, J.C. Healthcare 4.0 implementation: Opportunities and challenges in the healthcare sector. *Peer Rev.* **2023**, *5*, 163–182. [CrossRef]
10. Tortorella, G.L.; Fogliatto, F.S.; Sunder, M.V.; Vergara, A.M.C.; Vassolo, R. Assessment and prioritisation of Healthcare 4.0 implementation in hospitals using Quality Function Deployment. *Int. J. Prod. Res.* **2022**, *60*, 3147–3169. [CrossRef]
11. Al-Jaroodi, J.; Mohamed, N.; Abukhousa, E. Health 4.0: On the way to realizing the healthcare of the future. *IEEE Access* **2020**, *8*, 211189–211210. [CrossRef] [PubMed]
12. Goyal, S. Industry 4.0 in Healthcare IoT for Inventory and Supply Chain Management. In *Cyber-Physical Systems: Foundations and Techniques*; Wiley: Hoboken, NJ, USA, 2022; pp. 209–227.
13. Kalaria, C.; Singh, S.; Prajapati, B.G. Intelligent Healthcare Supply Chain. In *Human-Machine Interface: Making Healthcare Digital*; Wiley: Hoboken, NJ, USA, 2023; pp. 449–481.
14. Musamih, A.; Salah, K.; Jayaraman, R.; Arshad, J.; Debe, M.; Al-Hammadi, Y.; Ellahham, S. A blockchain-based approach for drug traceability in healthcare supply chain. *IEEE Access* **2021**, *9*, 9728–9743. [CrossRef]
15. Karatas, M.; Eriskin, L.; Deveci, M.; Pamucar, D.; Garg, H. Big Data for Healthcare Industry 4.0: Applications, challenges and future perspectives. *Expert. Syst. Appl.* **2022**, *200*, 116912. [CrossRef]
16. Boz, E.; Çizmecioğlu, S.; Çalık, A. A Novel MDCM Approach for Sustainable Supplier Selection in Healthcare System in the Era of Logistics 4.0. *Sustainability* **2022**, *14*, 13839. [CrossRef]
17. Hossain, M.K.; Thakur, V. Benchmarking health-care supply chain by implementing Industry 4.0: A fuzzy-AHP-DEMATEL approach. *Benchmarking Int. J.* **2021**, *28*, 556–581. [CrossRef]
18. Chatterjee, S.; Chaudhuri, R.; Gupta, S.; Mangla, S.K.; Kamble, S. Examining the influence of industry 4.0 in healthcare supply chain performance: Moderating role of environmental dynamism. *J. Clean. Prod.* **2023**, *427*, 139195. [CrossRef]
19. AbdelMouty, A.M.; Abdel-Monem, A.; Aal, S.I.A.; Ismail, M.M. Analysis the Role of the Internet of Things and Industry 4.0 in Healthcare Supply Chain Using Neutrosophic Sets. *Neutrosophic Syst. Appl.* **2023**, *4*, 33–42. [CrossRef]
20. Daú, G.; Scavarda, A.; Scavarda, L.F.; Portugal, V.J.T. The healthcare sustainable supply chain 4.0: The circular economy transition conceptual framework with the corporate social responsibility mirror. *Sustainability* **2019**, *11*, 3259. [CrossRef]
21. Rehman, O.U.; Ali, Y. Enhancing healthcare supply chain resilience: Decision-making in a fuzzy environment. *Int. J. Logist. Manag.* **2022**, *33*, 520–546. [CrossRef]
22. Fatorachian, H.; Kazemi, H. Impact of Industry 4.0 on supply chain performance. *Prod. Plan. Control.* **2021**, *32*, 63–81. [CrossRef]
23. Tortorella, G.L.; Fogliatto, F.S.; Espôsto, K.F.; Mac Cawley Vergara, A.; Vassolo, R.; Tlapa Mendoza, D.; Narayanamurthy, G. Measuring the effect of Healthcare 4.0 implementation on hospitals' performance. *Prod. Plan. Control.* **2022**, *33*, 386–401. [CrossRef]
24. Vishwakarma, A.; Dangayach, G.S.; Meena, M.L.; Gupta, S.; Luthra, S. Adoption of blockchain technology enabled healthcare sustainable supply chain to improve healthcare supply chain performance. *Manag. Environ. Qual. Int. J.* **2023**, *34*, 1111–1128. [CrossRef]
25. Kim, H.K.; Lee, C.W. Relationships among healthcare digitalization, social capital, and supply chain performance in the healthcare manufacturing industry. *Int. J. Environ. Res. Public Health* **2021**, *18*, 1417. [CrossRef]
26. Tortorella, G.L.; Saurin, T.A.; Fogliatto, F.S.; Rosa, V.M.; Tonetto, L.M.; Magrabi, F. Impacts of Healthcare 4.0 digital technologies on the resilience of hospitals. *Technol. Forecast. Soc. Chang.* **2021**, *166*, 120666. [CrossRef]
27. Hossain, M.K.; Thakur, V. A performance management framework for smart health-care supply chain based on industry 4.0 technologies. *J. Glob. Oper. Strateg. Sourc.* **2024**. [CrossRef]
28. Warty, R.R.; Smith, V.; Salih, M.; Fox, D.; Mcarthur, S.L.; Mol, B.W. Barriers to the diffusion of medical technologies within healthcare: A systematic review. *IEEE Access* **2021**, *9*, 139043–139058. [CrossRef]

29. Gadekar, R.; Sarkar, B.; Gadekar, A. Assessment of risks for successful implementation of Industry 4.0. *Recent Adv. Comput. Sci. Commun. (Former. Recent Pat. Comput. Sci.)* **2022**, *15*, 111–130. [CrossRef]
30. Khanna, N.N.; Maindarkar, M.A.; Viswanathan, V.; Fernandes, J.F.E.; Paul, S.; Bhagawati, M.; Ahluwalia, P.; Ruzsa, Z.; Sharma, A.; Kolluri, R.; et al. Economics of artificial intelligence in healthcare: Diagnosis vs. treatment. *Healthcare* **2022**, *10*, 2493. [CrossRef] [PubMed]
31. Tortorella, G.; Prashar, A.; Samson, D.; Kurnia, S.; Fogliatto, F.S.; Capurro, D.; Antony, J. Resilience development and digitalization of the healthcare supply chain: An exploratory study in emerging economies. *Int. J. Logist. Manag.* **2023**, *34*, 130–163. [CrossRef]
32. Tortorella, G.L.; Fogliatto, F.S.; Espôsto, K.F.; Vergara, A.M.C.; Vassolo, R.; Mendoza, D.T.; Narayanamurthy, G. Effects of contingencies on healthcare 4.0 technologies adoption and barriers in emerging economies. *Technol. Forecast. Soc. Chang.* **2020**, *156*, 120048. [CrossRef]
33. Adebisi, J.A.; Damilola, E.B.; Olubayo, M.B. A multicriteria framework for selecting information communication technology alternatives for climate change adaptation. *Cogent Eng.* **2022**, *9*, 2119537.
34. Wang, H.; Xu, Z.; Pedrycz, W. An overview on the roles of fuzzy set techniques in big data processing: Trends, challenges and opportunities. *Knowl.-Based Syst.* **2017**, *118*, 15–30. [CrossRef]
35. Liu, Y.; Eckert, C.M.; Earl, C. A review of fuzzy AHP methods for decision-making with subjective judgements. *Expert. Syst. Appl.* **2020**, *161*, 113738. [CrossRef]
36. Adebisi, J.; Babatunde, O. Green Information and Communication Technologies Implementation in Textile Industry Using Multicriteria Method. *J. Niger. Soc. Phys. Sci.* **2022**, *4*, 165–173. [CrossRef]
37. Iandolo, F.; Vito, P.; Fulco, I.; Loia, F. From health technology assessment to health technology sustainability. *Sustainability* **2018**, *10*, 4748. [CrossRef]
38. John, A.; Babatunde, O. Selection of Wireless Communication Technologies for Embedded Devices Using Multi-Critera Approach and Expert Opinon. *Niger. J. Technol. Dev.* 2023, in press.
39. Abbaspour, A.; Saremi, M.; Alibabaei, A.; Moghanlu, P.S. Determining the optimal human reliability analysis (HRA) method in healthcare systems using Fuzzy ANP and Fuzzy TOPSIS. *J. Patient Saf. Risk Manag.* **2020**, *25*, 123–133. [CrossRef]
40. Ansari, M.T.J.; Al-Zahrani, F.A.; Pandey, D.; Agrawal, A. A fuzzy TOPSIS based analysis toward selection of effective security requirements engineering approach for trustworthy healthcare software development. *BMC Med. Inform. Decis. Mak.* **2020**, *20*, 236. [CrossRef] [PubMed]
41. Salimian, S.; Mousavi, S.M.; Antucheviciene, J. An interval-valued intuitionistic fuzzy model based on extended VIKOR and MARCOS for sustainable supplier selection in organ transplantation networks for healthcare devices. *Sustainability* **2022**, *14*, 3795. [CrossRef]
42. Ighravwe, D.E. Assessment of Sustainable Maintenance Strategy for Manufacturing Industry. *Sustainability* **2022**, *14*, 13850. [CrossRef]
43. Ighravwe, D.; Aikhuele, D.; Fayomi, O.; Basil, A. Adoption of a multi-criteria approach for the selection of operational measures in a maritime environment. *J. Proj. Manag.* **2022**, *7*, 53–64. [CrossRef]
44. Aikhuele, D.O.; Ighravwe, D.E.; Akinyele, D. Evaluation of renewable energy technology based on reliability attributes using hybrid fuzzy dynamic decision-making model. *Technol. Econ. Smart Grids Sustain. Energy* **2019**, *4*, 16. [CrossRef]
45. Pandey, V.; Komal, K.; Dincer, H. A review on TOPSIS method and its extensions for different applications with recent development. *Soft Comput.* **2023**, *27*, 18011–18039. [CrossRef]
46. Zhang, Z.; Li, Z. Consensus-based TOPSIS-Sort-B for multi-criteria sorting in the context of group decision-making. *Ann. Oper. Res.* **2023**, *325*, 911–938. [CrossRef]
47. Motiwala, F.; Ezezika, O. Barriers to scaling health technologies in sub-Saharan Africa: Lessons from Ethiopia, Nigeria, and Rwanda. *Afr. J. Sci. Technol. Innov. Dev.* **2022**, *14*, 1788–1797. [CrossRef]
48. Zayyad, M.A.; Toycan, M. Factors affecting sustainable adoption of e-health technology in developing countries: An exploratory survey of Nigerian hospitals from the perspective of healthcare professionals. *PeerJ* **2018**, *6*, e4436. [CrossRef] [PubMed]
49. Adebayo, K.J.; Ofoegbu, E.O. Issues on E-health Adoption in Nigeria. *Int. J. Mod. Educ. Comput. Sci.* **2014**, *6*, 36. [CrossRef]
50. Omina Health. Nigeria Embraces Healthtech Solutions. Available online: https://insights.omnia-health.com/technology/nigeria-embraces-healthtech-solutions (accessed on 15 January 2024).
51. Ighravwe, D.E.; Oke, S.A. Selection of Outsourcing Relationship for a Maintenance System Using Fuzzy Axiomatic Design Principles and Fuzzy VIKOR. *Eng. Access* **2022**, *8*, 1–14.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.