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Redefining supply chain sustainability: introducing the context of extreme weather events

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Abstract

Purpose – Extreme weather events are on the rise around the globe. Nevertheless, it is unclear how these extreme weather events have impacted the supply chain sustainability (SCS) framework. To this end, this paper aims to identify and analyze the aspects and criteria to enable manufacturing firms to navigate shifts toward SCS under extreme weather events.

Design/methodology/approach – The Best-Worst Method is deployed and extended with the entropy concept to obtain the degree of significance of the identified framework of aspects and criteria for SCS in the context of extreme weather events through the lens of managers in the manufacturing firms of a developing country-Nigeria.

Findings – The results show that extreme weather preparedness and economic aspects take center stage and are most critical for overcoming the risk of unsustainable patterns within manufacturing supply chains under extreme weather events in developing country.

Originality/value – This study advances the body of knowledge by identifying how extreme weather events have become a significant moderator of the SCS framework in manufacturing firms. This research will assist decision-makers in the manufacturing sector to position viable niche regimes to achieve SCS in the context of extreme weather events for expected performance gains.

Keywords Supply chain management, Sustainability, Manufacturing industry, Extreme weather events

Paper type Research paper

1. Introduction

The importance of supply chain sustainability (SCS) has increased in recent decades due to population growth, resource shortages, consumption activities and increasing levels of waste and population (Orji and Ojadi, 2021; Tseng *et al.*, 2022). To ensure SCS, many research scholars advocate for developing a suitable framework through utilizing the triple-bottom-line (TBL) approach (Neri *et al.*, 2021; Orji and Ojadi, 2021), which generally classifies criteria under economic, environmental and social criteria. However, the occurrence of extreme weather events can make the implementation of SCS more intricate and complex. In recent times, extreme weather events have turned into a serious concern as climate change is exacerbating naturally occurring climate variability and thus adding to the uncertainty faced by weather-sensitive economic sectors (Bertrand *et al.*, 2015). Due to the direct and indirect disruptions, particularly, in supply chains exposed to extreme weather events, the interest in studying the consequences of this type of uncertainty is expected to grow enormously in the near future (Ehrenstein *et al.*, 2019). Indeed, the necessity to hedge against this type of uncertainty has become increasingly important given the occurrence of extreme weather events which are causing catastrophic disruptions to industrial operations and supply chains around the globe. For example, in 2011, heavy rainfall in regions of Thailand notable as the home to major automotive companies and the technology sector led to widespread flooding and severe supply chain disruptions that escalated and lasted the whole of the year 2012 (Haraguchi and Lall, 2015). More recently, in China, in just a few days in July 2021, Zhengzhou

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city received a year's worth of rain –a weather event seen as a "once in a thousand years" occurrence (Chik and Xue, 2021). Nigeria is not left out from these extreme occurrences as increased temperatures and heat waves are prevalent and noted to have a negative impact on the operations of various industrial sectors (Ojo and Baiyegunhi, 2021). The recent nationwide floods of 2012 in Nigeria (Akande *et al.*, 2017) and even the more recent nationwide floods of 2022, are pointers to the extreme precipitation being experienced in Nigeria. Thus, these few instances of extreme weather events illustrate the eminent requirement to assess the implications under this uncertainty type and improve sustainable performance in supply chains.

Surprisingly, there is a dearth of research in the extant literature on the implications of extreme weather events for sustainable supply chains despite their disastrous impact as emphasized by various research scholars (Bag *et al.*, 2022; Bergmann *et al.*, 2016; Panahi *et al.*, 2020). Even from the perspective of practitioners, companies encounter the problem of comprehending how to define a successful implementation of sustainable supply chains in response to extreme weather events' impacts. Verily, extreme weather events have been identified as the topmost risks to supply chain operations and are predicted to increase ten-fold magnitude in the future (Chandler, 2017; O' Marrah, 2017). With the projected increase in the frequency and intensity of extreme weather events, supply chains are at risk of disruption now more than ever, coupled with potentially dire economic, environmental and social consequences (Ehrenstein *et al.*, 2019). Yet still, the discussion on how to implement and improve sustainability in supply chains in the context of extreme weather events through a suitable framework is lacking. To bridge this gap, it is important to develop a decision framework to comprehensively understand the different aspects that are foremost to SCS improvements in the context of extreme weather events. Therefore, this study, in a pioneering effort, aims to develop and model a decision framework comprising of TBL dimensions, supply chain design and extreme weather preparedness aspects for implementing SCS in the context of extreme weather events.

Particularly, it is considered advisable for manufacturing companies to implement positive adaptation criteria to simultaneously confront extreme weather conditions and prevent significant increases in the negative effects of climate change (Cao *et al.*, 2022). This is because climate change is making extreme weather events more frequent and more intense with a negative influence on the financial performance of manufacturing organizations by resulting in sales decline (Bergmann *et al.*, 2016). In addition, increases in average temperatures have significant negative effects on the outputs of labor-intensive manufacturing companies (Cao *et al.*, 2022). As such, we focused this study on the Nigerian manufacturing sector. Evidently, the Nigerian manufacturing sector is an attractive case given its role in contributing to Nigeria's GDP of $244bn in 2011, which makes it one of the largest economies in Africa and arguably the largest market in Africa (Orji and Ojadi, 2021). There is also a high exposure of the Nigerian manufacturing sector to extreme weather events, with the recorded incidence of disasters like floods and drought in the past decades coupled with a prediction of a continued trend (NIMET, 2008). The flooding incidents of 2022 exacerbated the situation and begged the need to contextualize this study with Nigeria. For instance, the floods affected 92% of the entire country (i.e. 33 out of the 36 states), and the said states constitute the food basket of Nigeria on which most agro-based manufacturing companies (local and multinational) depend for input raw materials such as grains, cotton and tubers among others. The national emergency management agency in Nigeria termed the recent flooding the worst in decades and has warned that the situation could deteriorate further. The Post Disaster Need Assessment (PDNA) Report, following 2012 flood revealed that the total damage caused by the floods amounted to about $16.9bn, representing 1.4% of real GDP growth in that year (Nigeria, 2021). Also, severe drought is experienced in Nigeria as a result of deforestation and bush burning, and according to the International Monetary

Fund, Nigeria, just like most countries in Africa, experiences 33% of the world's drought due to rain-fed agriculture. Additionally, in 2022, the global disaster alert and coordination system alerted drought in Nigeria which lasted for one month and the drought indicator showed anomalies that are typical of extreme weather events.

Besides, the lands in the northern part of Nigeria have been rendered unproductive due to extensive cultivation and overgrazing compounded by desertification, while in the southern part of Nigeria, unpredictable and higher-intensity rainfalls are experienced, leading to displacement of communities. In fact, based on the 2021 Notre Dame Global Adaptation Index (https://gain.nd.edu/our-work/country-index/), Nigeria is ranked as the 53rd most susceptible country and also the 6th least ready in the world to adapt to climate change and extreme weather. In essence, climate change may increase the frequency and intensity of extreme weather events like floods, storms, ocean surges, droughts and wildfires in Nigeria. Climate projections suggest that there will be an increase in the number of extreme rainfall days and a considerable increase in the number of extreme heat days. Thus, agricultural ecosystems, freshwater and coastal resources, forests and biodiversity are all vulnerable to climate change impacts including desertification, increases in soil erosion, flooding and salt-water intrusion. As such, environmental resources are depleted in Nigeria, posing serious challenges to manufacturing firms, especially in the food sector. Furthermore, developing countries like Nigeria are most vulnerable to extreme weather events in their manufacturing supply chains and lack the basic insights as well as the capacity to mitigate the impact of extreme weather events (Furrer *et al.*, 2022; Obada *et al.*, 2023; Ojo and Baiyegunhi, 2021; Onyimadu and Uche, 2021). Likewise, a research gap remains on how extreme weather events have become a significant moderator of the framework for implementing SCS in manufacturing companies within such a context. Hence, this study proposes to answer the following research questions: (1) "Is extreme weather preparedness considered important for achieving supply chain sustainability under extreme weather events?" and (2) "How significant are the aspects and respective criteria for implementing sustainable supply chains in the context of extreme weather events within the Nigerian manufacturing industry?"

In answering the above-mentioned research questions, this study makes several significant theoretical and practical contributions. First, this study extends knowledge on SCS research to examine the implications of extreme weather events especially the key aspects relevant to developing a suitable implementation framework. In particular, this study introduces extreme weather preparedness, supply chain design as well as economic, environmental and social aspects as critical aspects to achieving sustainable supply chains within the context of extreme weather events (Bag *et al.*, 2022; Gupta *et al.*, 2022). Second, this study presents some discussions to shed light on the motivations for integrating these key aspects and their respective criteria and provides suggestions for managers in manufacturing companies to adequately plan improvement actions. Third, this study presents novelty in being focused on the manufacturing sector of a developing country – Nigeria – and as such contributes to studies on sustainability in the context of extreme weather within African emerging economies which currently lack such studies (NIMET, 2008; Ojo and Baiyegunhi, 2021; Onyimadu and Uche, 2021). This is in spite of African emerging economies being particularly vulnerable to extreme weather events as a result of inadequate infrastructure, lack of warning signs and variable adaptive capacity (Theron *et al.*, 2022). Fourth, this study presents a novelty in utilizing the Best-Worst Method (BWM) and the entropy concept to determine the objective weights as well as the degree of significance of the aspects and respective measures for SCS in the context of extreme weather events. The BWM can adequately simplify the data collection and processing as well as yield maximum consistency and reliability (Gupta *et al.*, 2022). On the other hand, the entropy concept determines weights based upon the data set itself and thus reduces decision bias and adds objectiveness to the decision process (Wu *et al.*, 2018). Thus, this study contributes to the application of multi-criteria decision-making models in the study of the implications of extreme weather events on SCS especially in the manufacturing sector.

The rest of this paper is organized as follows: Section 2 discusses extreme weather preparedness and SCS as well as identifies the key aspects of the proposed framework for implementing sustainable supply chains under extreme weather events. Section 3 presents the proposed research methodology for the current study with a detailed illustration of the modeling steps. Section 4 outlines the data collection process and the results of the study analysis. Section 5 presents the discussion of results and also provides theoretical and managerial implications to enlighten managers on the motivation for extreme weather preparedness in sustainable supply chains. The conclusions of the study coupled with the study limitations and future research directions are highlighted in Section 6.

2. Literature review

2.1 Supply chain sustainability and extreme weather preparedness

2.1.1 Supply chain sustainability. SCS is a type of information flow management that facilitates cooperation and collaboration among supply chain players and stakeholders while considering economic, social and environmental perspectives (Tseng *et al.*, 2022). It involves the integration of economic, environmental and social considerations with inter-organizational business systems to effectively and efficiently manage the material, information and capital flows involved in the different levels of the supply chain for improvements in organizational profitability, competitiveness and resilience (Mastrocinque *et al.*, 2022). In other words, SCS hinges on integrating the Triple Bottom Line (TBL) concept which defines the three main components of sustainability as social, environmental and social dimensions in supply chain management. This suggests that economic, social and environmental performance aspects must be simultaneously optimized for a successful implementation of SCS since these sustainability aspects have strong interdependencies (Darbari *et al.*, 2019). Moreover, although the implementation of SCS within the context of extreme weather events is fast evolving, the significance of extreme weather preparedness in such a context lacks related studies. Extreme weather preparedness usually entails proposing some novel ideas in processes, technologies and policies which can invariably result in the sustainability performance improvement of supply chain activities. Studies have proposed extreme weather preparedness strategies as having significant potential to mitigate the disastrous impact of extreme weather events in various business environments (Bag *et al.*, 2022; Gupta *et al.*, 2022). Furthermore, given the negative impact of extreme weather occurrences such as droughts, heat waves, flash floods, etc., extreme weather preparedness strategies coupled with TBL dimensions should be integrated into supply chain operations for utmost SCS.

2.1.2 Extreme weather preparedness. Extreme weather events have a massive impact on supply chain operations and thereby pose a huge requirement for firms to develop appropriate mechanisms to deal with these events (Bag *et al.*, 2022). Likewise, extreme weather preparedness is vital for firms to improve their organizational processes, including those for SCS, to lead to performance improvements in business environments that are prone to extreme weather occurrences. Apparently, the increasing frequency, severity and visibility of extreme weather events have increased public concern and research interest (Wang and Paul, 2020). However, most available published studies in extant literature focus on the response phase of extreme weather events with very few studies concentrating on the mitigation phase which comprises the preparedness activities (Martel *et al.*, 2017). Among the few studies, there exist published studies that discuss preparedness activities under extreme weather events in various domains like agriculture, food, humanitarian and construction sectors (Alem *et al.*, 2021; Bag *et al.*, 2022; Furrer *et al.*, 2022) as well as empirical evidence that analyzes the relationship between mitigating the negative impact of extreme weather and supply chain performance (Waters, 2011). The strategies associated with extreme weather preparedness mainly cover designing efficient infrastructure systems like thermal regulation systems and drainage systems, prepositioning essential supplies and resilience improvement of operational functions for minimizing the negative impacts of extreme weather occurrences (Wang and Paul, 2020). Furthermore, developing extreme weather preparedness strategies can support the operations of manufacturing firms and facilitate sustainability goals in the overall supply chain network (Furrer *et al.*, 2022).

However, there is a dearth of systematic studies that analyze the concept of extreme weather preparedness in manufacturing companies with regard to its significance during implementing SCS in the context of extreme weather events. To fill this literature gap, this study will provide a clear insight into the importance of preparedness strategies and other relevant practices including TBL and supply chain design indicators that can be implemented by manufacturers for utmost SCS gains under extreme weather events. With the increased frequency of extreme weather events (Alem *et al.*, 2021) and the growing popularity of sustainability (Orji and Ojadi, 2021), it is desirable to provide a better understanding of implementing sustainability objectives in supply chain networks under such events and advance knowledge in the field. In short, this study examines how extreme weather events have become a significant moderator of SCS in Nigerian manufacturing firms and, by so doing, provides insights into the significance of extreme weather preparedness for achieving SCS.

2.2 Identification of the proposed measures for supply chain sustainability in the context of extreme weather events

The conceptual aspects and criteria of the SCS framework in the context of extreme weather events were identified from the literature review. Then, we invited 35 managers in the Nigerian manufacturing sector to help in finalizing the identified aspects and criteria. Finalizing the criteria involved the managers indicating a "Yes" or a "No" if a particular system criterion was considered "relevant" or "irrelevant" respectively, for SCS in the Nigerian manufacturing sector. The managers were also asked during the finalization process to include additional study variables, if necessary, in order to ensure that no data was missing as well as to validate the sourced content. According to the managers' responses, additional criteria, namely, local environmental expertise and reuse and recycling packaging materials were included. Hence, the finalized aspects and criteria of the proposed framework for SCS under extreme weather events are presented in Table 1.

2.2.1 Extreme weather preparedness aspect. Adherence to climate policies (EX_1) such as carbon tax regulations can restrict carbon emissions and improve environmental performance for mitigating the impact of extreme weather events. *Efficient infrastructure systems* (EX_2) such as sustainable drainage systems are considered proactive measures to facilitate and justify extreme weather preparedness. *Well-designed hazard-resistant structures* (EX_3) include improved standards and sustainable construction practices to achieve resilience in hazard-prone areas (Adhikari *et al.*, 2020a). *Improved early warning and response system* (EX_4) is an innovative approach by which companies can sufficiently identify potential disasters and likewise respond to such events in order to minimize the negative impact on their business operations. *Strategic planning for essential supplies* (EX_5) indicates the conscious efforts to ensure continuous availability of emergency supplies at an affordable price and within the shortest possible period of time. *Employee health protective clothing* (EX_6) entails that protective clothing such as cooling vests, helmets, heat reflective suits and so on should be provided for employees to enable them to effectively carry out business operations even during extreme weather. *Employee training and development program* (EX_7) represents

Aspects	Criteria	References
Extreme weather preparedness (*EX*)	Adherence to climate change policies, e.g. carbon pricing Efficient infrastructure systems, e.g. thermal regulation systems, drainage systems and emergency generators Well-designed hazard-resistant structures and logistics facilities Improved early warning and response system Strategic planning for essential supplies shortage Employee health protective clothing Employee training and development program	Adhikari *et al.* (2020a), Alem *et al.* (2021), Bag *et al.* (2022), Cao *et al.* (2022), Furrer *et al.* (2022), Gupta *et al.* (2022), Haraguchi and Lall (2015), Martel *et al.* (2017), Wang and Paul (2020)
Supply chain design (*SC*)	Use of information technologies such as big data, blockchain and IoT Facility location and distribution management Inventory management Suppliers' integration and collaboration Business continuity plans	Bag *et al.* (2022), Gupta *et al.* (2022), Nath *et al.* (2020), Orji and Ojadi (2021), Sudusinghe and Seuring (2022), Tseng *et al.* (2022)
Environmental (*EN*)	Green product design Local environmental expertise Reuse and recycling materials for packaging Regular environmental auditing Effective debris management	Darbari *et al.* (2019), Gupta *et al.* (2022), Li *et al.* (2022), Mastrocinque *et al.* (2022), Orji and Ojadi (2021)
Social (*SO*)	Membership of social networks Safe work environment Absence of asymmetric information Improved brand image/reputation Improved cultural issues, e.g. improved local knowledge, low rate of corruption	Bag *et al.* (2022), Busch and Hansen (2021), Mani *et al.* (2020), Neri *et al.* (2021), Tseng *et al.* (2022), Zimmer *et al.* (2016)
Economic (*EC*)	Efficient production methods Effective time management/on-time delivery Improved quality of products Reduced operational costs Economic recovery programs	Kong *et al.* (2018), Mastrocinque *et al.* (2022), Neri *et al.* (2021), Orji and Ojadi (2021), Orji and U-Dominic (2022), Stevic *et al.* (2020)

Source(s): Table by authors

Table 1.
Proposed measures for implementing SCS in the context of extreme weather events

educational projects designed for employees to ensure building skills to effectively adapt to climate change and minimize the negative impact of extreme weather.

2.2.2 Supply chain design perspective. The use of information technologies (SC_1) such as big data, blockchain, Internet of Things and so on can be utilized to enhance sustainable performance in individual firms and supply chain networks, especially in the context of extreme weather (Bag *et al.*, 2022; Gupta *et al.*, 2022). *Facility location and distribution management* (SC_2) is essential for the efficient flow of materials, ensuring on-time delivery and improving cost-effectiveness under extreme weather events. *Inventory management* (SC_3) through control systems plays a critical role in decreasing the risks of shortage of essential supplies in the context of extreme weather events, as well as decreasing inventory-related costs. *Supplier's integration and collaboration* (SC_4) represents the conscious cooperation with suppliers which is highly critical for synchronizing operational activities that are related to information flow, material or product distribution and effective decision-making within supply chain networks (Tseng *et al.*, 2022). *Business continuity plans* (SC_6) are considered vital to mitigate and likewise respond to disasters since they encompass a framework of risk assessment and mitigation, continuity planning and plans for recovery from disruption.

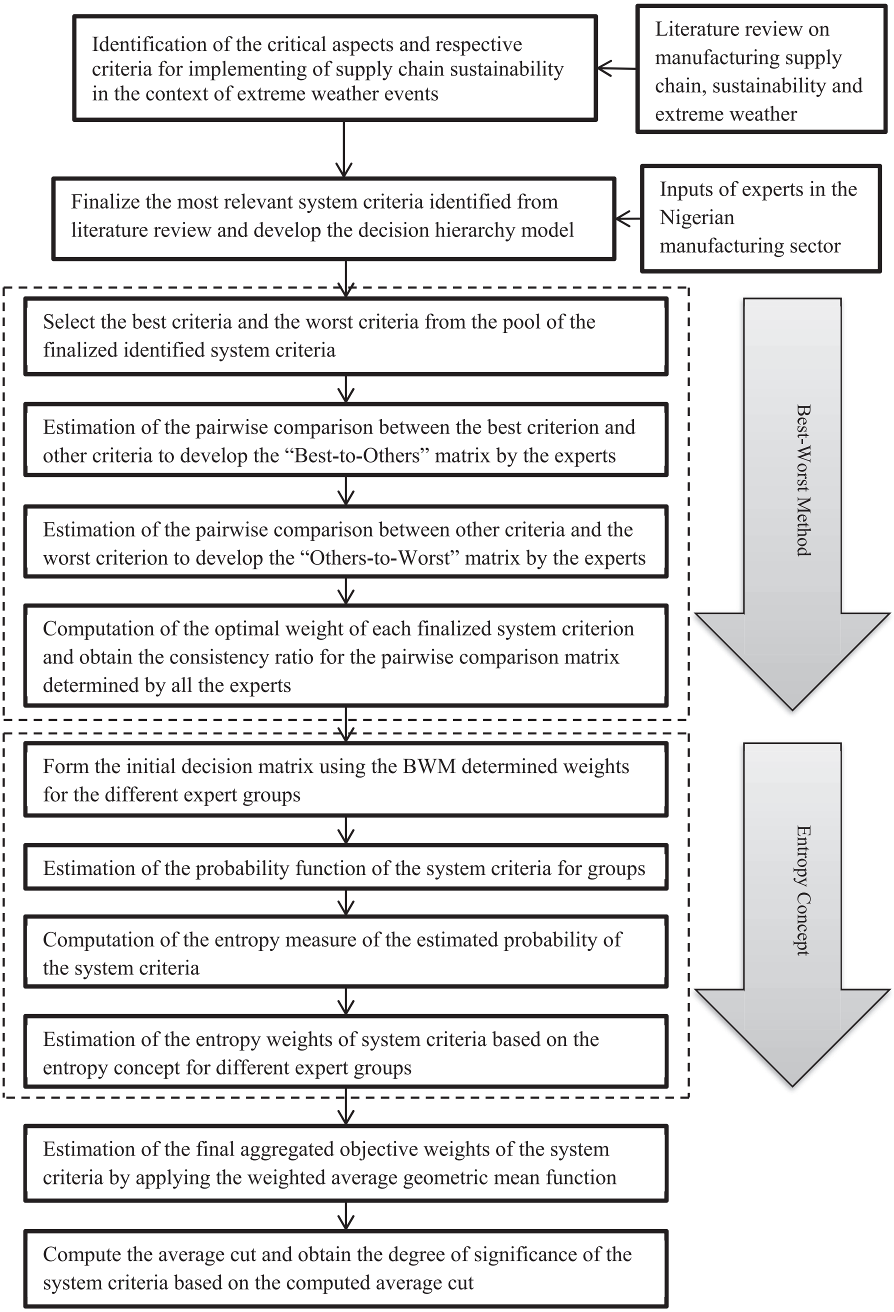
2.2.3 Environmental aspect. Green product design (EN_1) is highly critical for manufacturing firms to successfully achieve sustainability objectives in their supply chains. In fact, driven by the dual effect of push (from government regulations) and pull (from market demand), companies are strongly motivated to introduce green product design. *Local environmental expertise* (EN_2) is acquired through extensive personal observation and interaction with the local environment and also diffused among local resource users. *Reuse and recycling of packaging materials* (EN_3) is considered an inclusive approach by which consumers can effectively reuse and recycle the materials that are utilized in packaging finished products. *Regular environmental auditing* (EN_4) is considered an activity that is performed continuously to effectively assess environmental liabilities and also to improve the environmental performance of the supply chain enterprise. *Effective debris management* (EN_5) plays a critical role in achieving environmental performance improvements as well as minimizing the negative impact of extreme weather events on supply chain networks.

2.2.4 Social aspect. Membership of social networks (SO_1) is considered essential for sustainable development as well as for the continuation and acceleration of socio-economic transition especially in the early phases of sustainable innovation systems. *Safe work environment* (SO_2) is often considered to be a part of the social aspect even as a great deal of discussion on the importance of safety in the context of sustainable development is taking place. Asymmetric information reflects a difference between the demands of downstream participants and the involved suppliers' costs and contract designs (Tseng *et al.*, 2022). Thus, *absence of asymmetric information* (SO_3) is significant for SCS in manufacturing firms. *Improved brand image/reputation* (SO_4) is another critical issue to consider during decisions to implement SCS under extreme weather events. *Improved cultural issues* (SO_5) which represent ensuring that local knowledge is improved and a reduced corruption rate can facilitate a planned resolution to manage extreme weather and achieve sustainable development.

2.2.5 Economic aspect. Efficient production methods (EC_1) are among the primary concerns of manufacturing companies as they continuously strive to secure advanced technologies at the lowest cost and minimize the negative impact on the environment. *Effective time management* (EC_2) is another economic construct to consider since manufacturing companies require integrating just-in-time principles to minimize delivery resources (e.g. workers, equipment and others like delivery trucks, cranes and on-site storage areas) and environmental emissions (Kong *et al.*, 2018). *Improved quality of product* (EC_3) is a key point of product competitiveness which is closely related to product design and represents increasing the indices for conformance of products to prescribed standards and specifications. *Reduced operational costs* (EC_4) indicate providing adequate financial budgets for sustainability investments and also adopting relevant strategies (e.g. Lean Six Sigma) to radically reduce the cost of supply chain operations (Orji and U-Dominic, 2022). *Economic recovery programs* (EC_5) refer to financing strategies to return manufacturing companies to pre-extreme weather event functional levels or transition to a new more desirable state.

3. Methodology

This study employs a proposed decision model that involves integrating the BWM with the entropy concept to analyze the critical aspects and specific criteria for implementing manufacturing SCS in the context of extreme weather events. An illustration of the research modeling framework employed in this study is shown in Figure 1.



Source(s): Figure by authors

Figure 1.
Proposed research framework

3.1 Application of best-worst method and entropy concept

From a methodological viewpoint, this study makes contributions to the research domain on the analysis and estimation of the aggregated objective weights of system criteria as well as obtaining their degree of significance. The BWM is considerably a superior decision model due to its higher consistency ratio and other evaluation criteria like total deviation, minimum violation and conformity (Rezaei, 2015). It is based on comparing the best criteria with other criteria and also, all the criteria are compared with the worst criteria (Ekinci *et al.*, 2024). BWM is notable for its minimum violation, consistency and total deviation, making it more preferred than the analytical hierarchy process (AHP) (Mi *et al.*, 2019). The relatively small datasets that are needed for BWM computations can produce more consistent results unlike the AHP (Gupta *et al.*, 2023; Orji and Ojadi, 2023). Besides, BWM employs the two-vector approach in its computational steps which makes it easier than the AHP that uses a full matrix-based approach, which is more complex and time-consuming (Kusi-Sarpong *et al.*, 2021). BWM is a data-efficient method that can produce reliable results and also determine optimal weight through mathematical modeling (Alidoosti *et al.*, 2021; Paul *et al.*, 2023). In fact, BWM is considered more preferable than other multi-criteria decision-making (MCDM) methods such as AHP (Feng *et al.*, 2023), decision-making trial and evaluation laboratory (DEMATEL) (U-Dominic *et al.*, 2021; Orji, 2024), multiple objective optimization based on the ratio analysis plus full multiplicative form (MULTIMOORA) (Orji and Ojadi, 2023), technique for order of preference by similarity to ideal solutions (TOPSIS) (Bajpai *et al.*, 2023) and preference ranking organization method for enrichment evaluations (PROMETHEE) (Tong *et al.*, 2022), due to its consistency in rational decision-making. Since the critical aspects and specific criteria for implementing manufacturing SCS in extreme weather events interrelate and depend on each other, it is necessary to apply a decision method to effectively consider these interrelationships. Notably, DEMATEL and AHP can consider interrelationships between system criteria, but then, BWM outperforms both methods to effectively obtain the pairwise comparison between system criteria (Gupta *et al.*, 2023). Thus, BWM has been widely applied in various domains including in the sustainable supply chain management field (Ekinci *et al.*, 2024; Gupta *et al.*, 2023; Kusi-Sarpong *et al.*, 2021; Tseng *et al.*, 2022).

Moreover, most MCDM methods lack the capability to adequately address the equal weightage challenge in decision problems, reducing the accuracy of study findings. However, among the MCDM methods such as BWM, DEMATEL, AHP, etc. the entropy concept is a popular MCDM method that can overcome this equal weighting challenge, due to its superior computational strengths (Shang *et al.*, 2022; Tavana *et al.*, 2021). Essentially, the main advantages of the entropy concept are that, firstly, it generates results in a set of common weights across decision-making units that allow for complete comparison and ranking of the decision units thereby computationally efficient and, second, it is simple and also easy to implement (Karagiannis and Karagiannis, 2020). Likewise, Zeng *et al.* (2020) used the entropy concept in the presence of a neutrosophic set to overcome the equal weightage problem and obtain the objective weights of suppliers. Adhikari *et al.* (2020b) utilized the entropy concept together with data envelopment analysis (DEA) and semi-variance to select players. Also, Dos Santos *et al.* (2019) proposed an Entropy-TOPSIS framework to analyze and select green suppliers in the furniture sector. Ojadi *et al.* (2023) used the entropy concept to select sustainable suppliers based on CSR. Besides, Levner and Alexander (2015) applied the entropy concept to identify the risk factors in supply chain management. Thus, the application of the entropy concept in the SCS domain is growing. But then, there is still a dearth of studies that combined the entropy concept with BWM to present a more comprehensive methodology that considers interrelationships between criteria and overcomes the equal weightage problem. Therefore, to bridge these research gaps, this study proposes to apply BWM and entropy concept, to develop an effective methodology which can consider the interrelationships between the system criteria for implementing SCS in the context of extreme weather events as well as overcome equal weightage problem by obtaining their objective weights. In other words, the developed methodology based on BWM and entropy concept, leverages the numerous benefits and advantages of these two models.

3.2 Best-worst method

The BWM is a prominent multi-criteria decision-making model which is capable of measuring and prioritizing the best and worst criteria for the process of decision-making (Tseng *et al.*, 2022). It is also notable for its result consistency during rational decision-making and, as such, is considered preferable to other multi-criteria decision-making models (Kusi-Sarpong *et al.*, 2021). Thus, we have applied BWM in this study to estimate the initial weights of the system criteria based on the experts' evaluations. In short, the steps involved in utilizing the BWM to obtain the criteria initial weights are as follows:

Step 1: Select the best criteria and the worst criteria from the pool of the finalized identified system criteria

In this step, the experts choose the best criteria as well as the worst criteria from the available pool of finalized system criteria (see Table 1).

Step 2: Estimation of the pairwise comparison between the best criterion and other criteria to develop the "Best-to-Others" matrix by the experts

Here, the experts determine the pairwise comparisons between the best criteria and other criteria with the aid of a 9-point linguistic scale shown in Table 2. The resulting BWM matrix is known as "Best-to-Others" matrix and is presented in Eq. (1) as follows:

$$C_{Bn} = (r_{B1}, r_{B2}, r_{B3} \ldots r_{Bn}) \tag{1}$$

where C_{Bn} represents the best-to-worst matrix while r_{Bn} denotes the expert's preferential judgment of the best criteria B over other criteria.

Step 3: Estimation of the pairwise comparison between other criteria and the worst criterion to develop the "Others-to-Worst" matrix by the experts

Within this step, the experts estimate the pairwise comparisons between the other criteria and the worst criteria using linguistic values. The resulting BWM matrix is known as "Others-to-Worst" matrix and is presented in Eq. (2) as follows:

$$C_{Wn} = (r_{W1}, r_{W2}, r_{W3} \ldots r_{Wn})^T \tag{2}$$

where C_{Wn} represents the best-to-worst matrix while r_{Wn} denotes the expert's preferential judgment on the importance of other criteria over the worst criteria W.

Linguistic attributes	Values
Equally important to	1
Equal to moderately more important to	2
Moderately more important to	3
Moderately to strongly more important to	4
Strongly more important to	5
Strongly to very strongly more important to	6
Very strongly more important to	7
Very strongly to extremely more important to	8
Extremely more important to	9

Source(s): Table by authors

Table 2. Linguistic scale for BWM-based evaluations

Step 4: Computation of the optimal weight of each finalized system criterion and obtain the consistency ratio for the pairwise comparison matrix determined by all the experts

In this step, the optimal weight $(o_1^*, o_2^*, \ldots, o_n^*)$ of the system criteria is represented by each pair of $\left(\frac{o_B}{o_n}\right)$ and $\left(\frac{o_n}{o_W}\right)$. Then, the BWM minimizes the maximum of the set of criteria $\left\{\left|\frac{o_B}{o_n}\right|, \left|\frac{o_n}{o_W}\right|\right\}$, in such a way that the maximum absolute difference (*MAD*) of the sets of system is minimized as presented in Eq. (3)

$$MAD = \left(\left|\alpha_n - \frac{o_B}{o_n}\right|, \left|\beta_n - \frac{o_n}{o_B}\right|\right) \tag{3}$$

where (α_n, β_n) is calculated as $\alpha_n = \left(\frac{o_B}{o_n}\right)$ and $\alpha_n = \left(\frac{o_B}{o_n}\right)$.

Then, the min-max model is presented in Eq. (4) as follows:

$$\left\{\begin{array}{l} \min \varepsilon \\ \left|\alpha_n - \dfrac{o_B}{o_n}\right| \leq \varepsilon \\ \left|\beta_n - \dfrac{o_n}{o_W}\right| \leq \varepsilon \\ \sum_{n=0} o_n^* = 1 \\ o_n^* \geq 0 \end{array}\right\} \tag{4}$$

Hence, $(o_1^*, o_2^*, o_3^* \ldots, o_n^*)$ are estimated as the optimal value of ε. Likewise, the consistency ratio (*CS*) for the pairwise comparison is obtained as shown in Eq. (5).

$$CS = \varepsilon / IC \tag{5}$$

where *IC* signifies the index of consistency which is the highest possible value of $\varepsilon(\max \varepsilon)$. The consistency ratio ranges from 0 to 1 and the closer a computed value is to 0, the more desirable and consistent is the pairwise comparison (Gupta *et al.*, 2023). The resulting BWM weights are utilized as inputs for the entropy concept-based computations of the entropy weights of system criteria for the expert groups.

3.3 Entropy concept

The entropy concept has a central role in information theory and provides an objective weighting that fully exploits the data information and particularly gives more weight to component indicators with larger variation across decision-making units (Karagiannis and Karagiannis, 2020). Hence, in this study, we have applied the entropy concept to estimate the final aggregated objective weights of the aspects and their respective criteria as well as their degree of significance. The steps involved in the entropy concept are as follows:

Step 1: Form the initial decision matrix using the BWM-determined weights for the different expert groups

Within this step, the initial decision matrix is developed from the outputs of the BWM computations and formulated with $d = \{d_1, d_2, \ldots d_n\}$ representing the set of alternatives,

$h = \{h_1, h_2, \ldots h_n\}$ representing the set of criteria and w_{ij} representing the evaluation score of the criterion with respect to the different alternatives/expert groups. Also, the information on the entropy weights is represented by $e = \{e_1, e_2, \ldots, e_n\}^u$ which translates to $0 \leq e_j \leq 1$ and $\sum_{j=1}^{n} e_j$.

Step 2: Estimation of the probability function of the system criteria for the expert groups

In this step, the probability function k_{ij} of the criterion for the expert groups is derived from Eq. (6).

$$k_{ij} = \frac{o_{ij}}{\sum_{i=1}^{n} o_{ij}} \tag{6}$$

where o_{ij} is the BWM determined weights of the system criteria.

Step 3: Computation of the entropy measure of the estimated probability of the system criteria

In this step, the entropy measure of the probability functions can be calculated using Eq. (7).

$$Q_j = -z \sum_{i=1}^{n} k_{ij} \ln k_{ij} \tag{7}$$

where $z = \frac{1}{\ln n}$ and assuming $k_{ij} = 0$, then $k_{ij} \ln k_{ij} = 0$

Step 4: Estimation of the entropy weights of system criteria based on the entropy concept for different expert groups

Within this step, the entropy weights of the system criteria are determined for different expert groups based on the entropy concept as shown in Eq. (8).

$$e_j = \frac{1 - Q_j}{\sum_{j=1}^{m} (1 - Q_j)} \tag{8}$$

where $0 \leq e_j \leq 1, \sum_{j=1}^{m} e_j = 1$.

Step 5: Obtain the final aggregated objective weights

In this step, the final aggregated objective weights of the indicators are computed through applying the weighted geometric mean function GM^{ζ} as shown in Eq. (11).

As initial definitions, let θ_1 and θ_2 be any two real numbers, then Dombi T-norm and T-conorm of the numbers θ_1 and θ_2 are defined and presented as shown in Eq. (9) and (10) (Dombi, 2009):

$$\Delta_D(\theta_1, \theta_2) = \frac{1}{1 + \left\{ \left(\frac{1-\theta_1}{\theta_1} \right)^{\xi} + \left(\frac{\theta_2}{1-\theta_2} \right)^{\lambda} \right\}^{\frac{1}{\zeta}}} \tag{9}$$

$$\Delta_D^c(\theta_1, \theta_2) = 1 - \frac{1}{1 + \left\{ \left(\frac{\theta_1}{1-\theta_1} \right)^{\zeta} + \left(\frac{\theta_2}{1-\theta_2} \right)^{\zeta} \right\}^{\frac{1}{\zeta}}} \tag{10}$$

where ζ > 0 and $(\theta_1, \theta_2) \in [0,1]$. Based on the definitions presented in Eq. (9) and (10), the weighted geometric mean function GM^{ξ} can be defined as shown in Eq. (11).

$$GM_j^{\xi=1}(e_{j1}, e_{j2}, \ldots, e_{jm}) = \sum\nolimits_{j=1}^{m} e_j \times \frac{\sum\nolimits_{j=1}^{m} e_j}{1 + \left\{ e_j \left(\frac{1-f(e_j)}{f(e_j)} \right)^{\lambda} \right\}^{\frac{1}{\lambda}}} \tag{11}$$

where λ which indicates the importance weights of each expert group while $f(e_j)$ represents the additive normalized scores of the entropy weight coefficients and $e_j = (e_{j1}, e_{j2}, \ldots, e_{jm})^T$ is the vector weight coefficient of the system criteria.

Step 6: Compute the average cut and determine the degree of significance of criteria

Finally, the degree of significance of the aspects and their respective criteria will be determined with the aid of the average cut/arithmetic mean (*M*) of the system criteria. Thus, the most significant aspects and most significant criteria have their final aggregated objective weights that are higher in value than the arithmetic mean (*M*).

4. Application of the proposed model

This study explores the key aspects and elements that can facilitate the successful implementation of SCS under extreme weather events, especially in manufacturing firms. The process of data collection in the Nigerian manufacturing sector and the subsequent analysis of the proposed aspects and measures for SCS are presented in this section.

4.1 Data collection

The implication of the proposed modeling framework based on the BWM is illustrated through Nigerian manufacturing companies identified from the records of the Manufacturing Association of Nigeria (MAN) from April 2022 to November 2022. The considered manufacturing companies were selected based on their strong commitment to achieve SCS in the context of prevailing extreme weather conditions within the Nigerian clime. Notably, among the various industries that make up the Nigerian industrial sector, food and beverage manufacturing firms make up the highest composition with about 35% (NBS, 2014). Indeed, the business of food and beverages manufacturing in Nigeria is booming at a fast pace owing to market needs and the number of customers (Ogunjuyigbe *et al.*, 2015). Thus, in this study, we have specifically selected indigenous Nigerian companies that fall within the food and beverage manufacturing sector, having the potential to provide significant value through food and beverage products. Initially, we selected 42 Nigerian food and beverage manufacturing firms and then contacted these firms to request for their participation in the study survey. The top-level managers who oversee the firms' decisions to implement innovative strategies for SCS were the target group utilized in this study. After, the initial contact with the selected firms, 35 managers out of 42 indicated their willingness to participate in the survey, a response rate of 83.3% which generally shows that the level of variation in terms of firm-specific characteristics is satisfactory (Yasmin *et al.*, 2020). The sample size is sufficient for accurate analysis and result generalization since there is research evidence that the proposed decision model in this study is based on the BWM and the entropy concept can provide accurate results with a smaller sample size (Ekinci *et al.*, 2024; Kusi-Sarpong *et al.*, 2021; Ojadi *et al.*, 2023; Tseng *et al.*, 2022). Besides, the sample size, even though not presenting a broad-based study, can provide generalizable results since the implementation of SCS in the Nigerian food and manufacturing industry is still at a nascent stage. Moreover, we applied a purposive sampling method, to consider only the food and beverages manufacturing firms that were committed to SCS in the context of extreme weather events and whose managers were knowledgeable in such aspects, for possible generalization of the results from the survey. The respondents in the study survey have between 5 and 20 years of experience as top-level managers in the food and beverage manufacturing industry and have job functions as managing director, distribution/logistics manager, procurement manager, supply chain manager and warehousing manager. Other relevant demographic attributes of the managers and the case firms are presented in Table 3. Notably, as observed from the demographic attributes of the managers shown in Table 3, the gender role is not balanced. This corroborates past studies that suggest that in countries in the Sub-Saharan Africa, like Nigeria, only 1 of 26 women make it to senior management, unlike the men, due to cultural and traditional beliefs (IFC, 2018; Nyeadi *et al.*, 2021). Many firms across the globe still struggle to appoint even a single woman to their boards (AFDB, 2015).

Data were sourced from the study respondents with the aid of two sets of questionnaires. The aim of the first set of questionnaires is to ascertain information on the finalization of study criteria and ensure content validity (see Section 2.3), while the second set is to provide insight into the relative importance of the criteria framework for SCS under extreme weather

Table 3. Demographic characteristics of the study respondents and case firms

Demographic characteristic	Number of respondents
Age	
30–40	8
41–50	20
51–60	7
Gender	
Male	28
Female	7
Highest educational qualification	
High school certificate	1
Foundation degree (HND)	5
Bachelor degree	28
Postgraduate degree	1
Years of experience	
5–10	25
11–20	10
Managerial position	
Distribution/Logistics manager	5
MD/CEO	3
Procurement manager	11
Supply chain manager	7
Warehousing manager	9
Annual revenue (million naira)	
50–200	17
210–500	16
Above 500	2
Firm size (number of employees)	
100–500	30
501–1,000	5

Source(s): Table by authors

events. In addition, the two sets of questionnaires were designed to include questions about the demographic characteristics of the study respondents. Several measures were taken to improve the validity and quality of the designed questionnaire, increase experts' response rate and minimize non-response bias. For instance, a pilot study was initially conducted which involved seven experts in academia, having more than 10 years of post-PhD research experience in SCS studies. The designed questionnaires were further refined using the feedback from the pilot study to improve their validity and ensure the survey results accuracy. Additional measures such as phone call conversations, email reminders and field visits were also conducted to increase the response rate of the managers. Also, a statistical test namely *t*-test (Orji and Liu, 2020) was done by computing the statistical difference between two demographic attributes (see Table 3) between the first and second half of the period of the survey to minimize non-response bias and increase result generalizability. The computed *t*-test score of 0.061 suggests that non-response bias is minimized since there is no significant statistical difference between the considered attributes.

4.2 Analysis of the key aspects and respective criteria for supply chain sustainability in the context of extreme weather events using the proposed model

The decision hierarchy model for analyzing the implications of extreme weather events on implementing SCS is illustrated in Figure 2. According to Figure 2, there were three levels in the decision hierarchy; the first level indicated the purpose of the research study which was to examine the implications of extreme weather events on SCS. The second level of the decision model signifies the key aspects of implementing SCS in the context of extreme weather events while the third level showed the respective elements.

4.2.1 Best-worst method results. The linguistic scale presented in Table 2 was utilized for the pairwise comparison, conducted to determine the relative importance of the considered aspects and respective measures/criteria. Particularly, thirty-five experts in this study determine the best and worst criteria from the pool of system criteria. The experts obtained the level of importance amongst the aspects as well as the specific measures with the aid of pairwise comparison matrix designed from the BWM, comprising of best-to-others and others-to-worst matrices. The pairwise comparison of the considered aspects, derived from the preferential judgments of one of the experts was presented in Table 4. Likewise, the preferential judgments on the pairwise comparison for the specific measures in each of the aspects were determined by the experts. Table 5 shows the preferential judgments on the pairwise comparison for the specific measures as determined by an expert. Then, using Eq. (1)–(5) in the BWM Solver, the weights of the aspects were obtained for each of the experts considered in this study. Then, using Eq. (1)–(5) in the BWM Solver, the weights of the aspects were obtained for each of the experts considered in this study. The BWM weight outputs obtained for each expert were aggregated in groups representing the similarities in managerial roles. The aggregated outputs were utilized as inputs for the entropy model applied in this study.

4.2.2 Entropy concept results. This study employs the entropy concept to determine the final aggregated objective weights of the system criteria based on their initial/subjective weights derived from the BWM-based computations for the different expert groups. In particular, the BWM weights of the system criteria for the different expert groups were utilized in Eq. (6) to firstly determine the probability functions. Furthermore, the entropy measures of the probability functions of the system criteria were computed using Eq. (7) for the different expert groups. Thus, the entropy measures of the probability functions of the aspects for the considered expert groups are shown in Table 6 while those of their respective criteria are presented in Table 7. Also, the entropy weights of the system criteria were computed for the expert groups using Eq. (8).

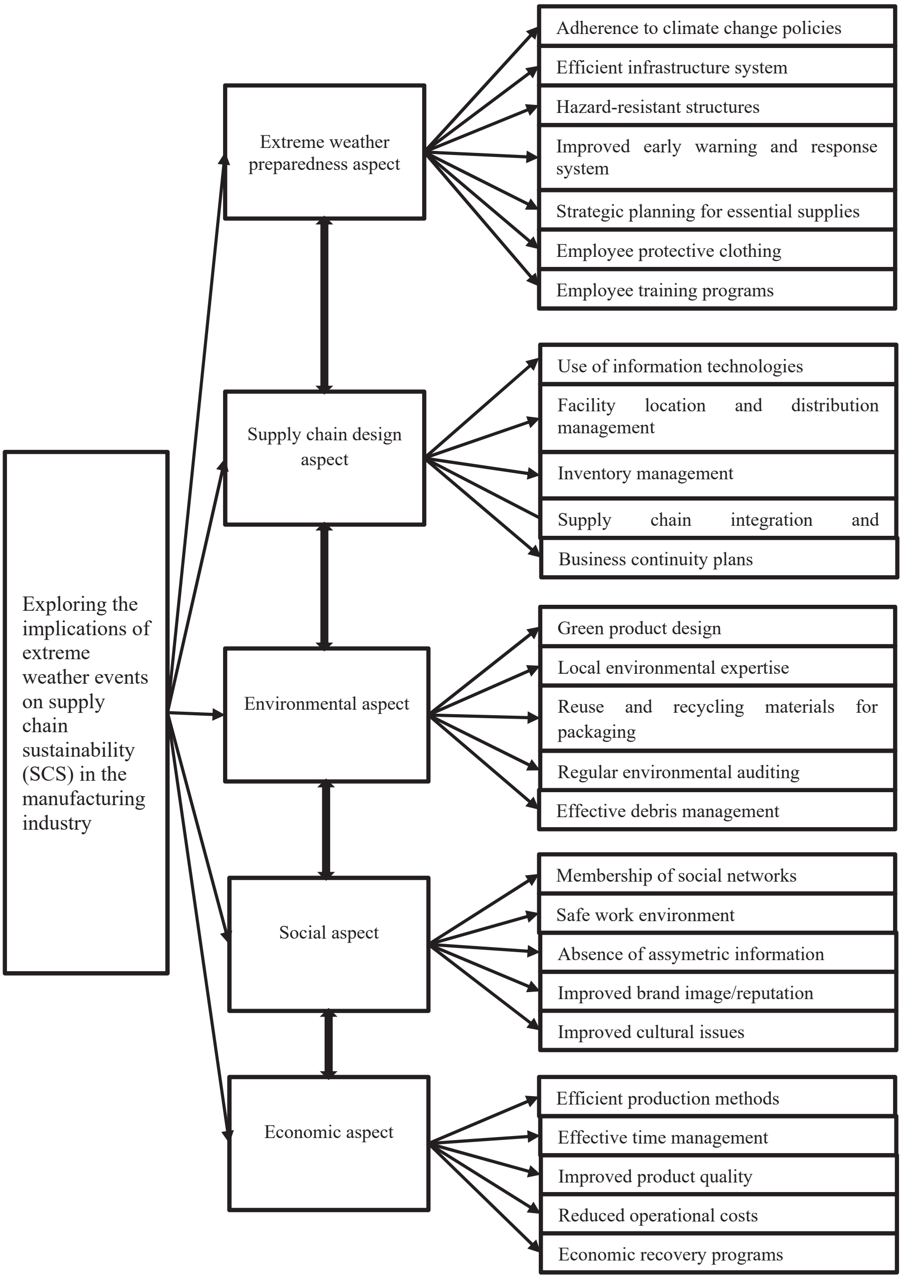


Figure 2.
Decision hierarchy model for the implications of extreme weather events on SCS

Source(s): Figure by authors

Additionally, we introduced weighted geometric mean function in the entropy concept to assist in predicting the final aggregated objective weights of the aspects and respective criteria using the entropy weights determined for the expert groups. Thus, the final aggregated objective weights of the system criteria were computed using Eq. (9)–(11). For example, since five expert groups are considered in this study, we assume assign same values of importance $\lambda_j = 1$. Hence, using the computed entropy weight scores, Eq. (9)–(11) and $\zeta = 1$, the final aggregated objective weights can be computed for extreme weather preparedness aspect (*EX*) as follows:

$$GM^{\zeta}=^{1}(0.658,\ldots,0.357) = 1.901\frac{1.901}{1+\left(0.658\times\left(\frac{1-\frac{0.658}{1.901}}{\frac{0.658}{1.901}}\right)^{1}\ldots+0.357\left(\frac{1-\frac{0.357}{1.901}}{\frac{0.357}{1.901}}\right)^{1}\right)^{\frac{1}{1}}}$$

$$= 0.387$$

The same process was utilized to compute the final aggregated weights of the remaining four aspects and twenty-seven specific criteria considered in this study. Table 8 shows the computed final aggregated weights and ranking of the aspects and their respective criteria.

Finally, in order to determine the most significant system criteria, the average cut (*M*) value was computed for the aspects and their respective criteria as 0.2 and 0.037 respectively. Based on the average cut (*M*), the most significant aspects which are invariably those guaranteed to ensure SCS in the context of extreme weather events are "extreme weather preparedness" and "economic" aspects.

5. Discussion

5.1 Degree of significance of aspects and respective criteria

An illustration of the final aggregated weights, obtained for the aspects relevant to implementing SCS in the context of extreme weather events within Nigerian food manufacturing firms and the computed average cut is shown in Figure 3. According to the results in Figure 3, the most significant aspects to enhancing sustainable performance in manufacturing supply chains in the context of extreme weather events are *extreme weather preparedness* and the *economic aspect*. This is in line with previous studies that suggest the significance of building extreme weather preparedness, in the pursuit of sustainable development in the supply chains (Alem *et al.*, 2021; Bag *et al.*, 2022; Gupta *et al.*, 2022). However, this contradicts the traditionally held belief that only the social, economic and environmental dimensions, based on the TBL approach, are the most significant to sustainability. In fact, the results in this study, shows that extreme weather preparedness takes centre stage for implementing SCS under extreme weather events. Hence, this study

Best to others	EX	SC	EN	SO	EC
Best criteria: EX	1	2	8	4	3
Others to worst	Worst Criteria: EN				
EX	7				
SC	5				
EN	1				
SO	2				
EC	3				

Source(s): Table by authors

Table 4.
Preferential judgments of an expert on the pairwise comparisons of the aspects of implementing SCS under extreme weather events

Extreme weather preparedness strategies							
Best to others	EX_1	EX_2	EX_3	EX_4	EX_5	EX_6	EX_7
Best criteria: EX_5	3	5	7	9	1	5	9
Others to worst							
Worst criteria: EX_7							
EX_1	3						
EX_2	7						
EX_3	1						
EX_4	5						
EX_5	9						
EX_6	7						
EX_7	1						

Supply chain design criteria					
Best to others	SC_1	SC_2	SC_3	SC_4	SC_5
Best criteria: SC_2	2	1	3	3	4
Others to worst					
Worst criteria: SC_5					
SC_1	8				
SC_2	4				
SC_3	3				
SC_4	5				
SC_5	1				

Environmental criteria					
Best to others	EN_1	EN_2	EN_3	EN_4	EN_5
Best criteria: EN_4	3	7	5	1	9
Others to worst					
Worst criteria: EN_5					
EN_1	7				
EN_2	9				
EN_3	1				
EN_4	9				
EN_5	1				

Social criteria					
Best to others	SO_1	SO_2	SO_3	SO_4	SO_5
Best criteria: SO_1	1	7	9	5	3
Others to worst					
Worst criteria: SO_3					
SO_1	9				
SO_2	1				
SO_3	1				
SO_4	9				
SO_5	5				

Economic criteria					
Best to others	EC_1	EC_2	EC_3	EC_4	EC_5
Best criteria: EC_3	3	7	1	5	9
Others to worst					
Worst criteria: EC_5					
EC_1	3				
EC_2	9				
EC_3	9				
EC_4	7				
EC_5	1				

Source(s): Table by authors

Table 5. Pairwise comparison of the specific criteria by one of the experts

exists to provide right guidelines to the managers in the Nigerian food and beverages manufacturing industry, for channelling scare resources, to develop the measures that have strong potentials, for hedging against extreme weather events. This is because Nigeria has been identified as one of the countries in the African region that are most vulnerable to climate change (Ani *et al.*, 2022). Gloomily, Nigeria is classified as one of the ten most vulnerable countries to the negative impacts of extreme weather events (Climate Scorecard, 2019). Indeed, the recurring environmental disasters manifest as desertification, flooding and increased rainfalls in various parts of Nigeria, have resulted in negative impact on the

Aspects	Entropy probability by expert group 1	Entropy probability by expert group 2	Entropy probability by expert group 3	Entropy probability by expert group 4	Entropy probability by expert group 5
EX	0.442	0.745	0.954	0.963	0.829
SC	0.117	0.975	0.905	0.978	0.877
EN	0.028	0.969	0.808	0.966	0.963
SO	0.042	0.988	0.913	0.732	0.906
EC	0.042	0.962	0.972	0.892	0.946

Source(s): Table by authors

Table 6. Entropy measures of probability functions of the aspects for different expert groups

Criteria	Entropy probability by expert group 1	Entropy probability by expert group 2	Entropy probability by expert group 3	Entropy probability by expert group 4	Entropy probability by expert group 5
EX_1	0.391	0.994	0.975	0.983	0.910
EX_2	0.867	0.911	0.937	0.992	0.893
EX_3	0.826	0.809	0.875	0.985	0.816
EX_4	0.837	0.934	0.901	0.869	0.680
EX_5	0.605	0.977	0.952	0.975	0.910
EX_6	0.801	0.998	0.856	0.947	0.764
EX_7	0.827	0.584	0.911	0.877	0.818
SC_1	0.795	0.996	0.898	0.863	0.767
SC_2	0.855	0.961	0.809	0.804	0.779
SC_3	0.878	0.997	0.951	0.959	0.823
SC_4	0.964	0.987	0.966	0.928	0.895
SC_5	0.685	0.982	0.879	0.939	0.809
EN_1	0.926	0.931	0.911	0.981	0.909
EN_2	0.712	0.976	0.830	0.963	0.779
EN_3	0.982	0.995	0.867	0.813	0.683
EN_4	0.950	0.994	0.899	0.933	0.914
EN_5	0.944	0.998	0.920	0.880	0.921
SO_1	0.803	0.997	0.893	0.819	0.868
SO_2	0.763	0.994	0.935	0.996	0.857
SO_3	0.975	0.992	0.934	0.921	0.849
SO_4	0.716	0.985	0.883	0.919	0.842
SO_5	0.935	0.990	0.851	0.866	0.812
EC_1	0.885	0.996	0.897	0.971	0.799
EC_2	0.780	0.996	0.922	0.820	0.871
EC_3	0.737	0.926	0.892	0.886	0.821
EC_4	0.952	0.943	0.906	0.842	0.864
EC_5	0.884	0.984	0.911	0.954	0.900

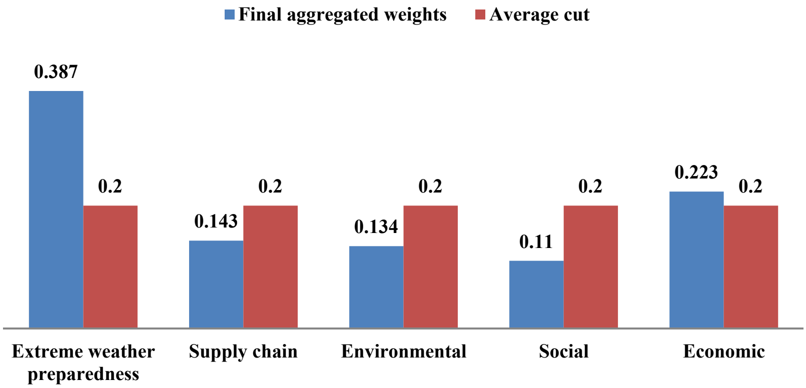
Source(s): Table by authors

Table 7. Entropy measures of probability functions of the specific criteria for different expert groups

Aspects	Final aggregated weights	Rank	Criteria	Final aggregated weights	Rank
Extreme weather preparedness (*EX*)	0.387	1	Adherence to climate change policies (EX_1)	0.0249	23
			Efficient infrastructure system, e.g. drainage systems (EX_2)	0.1863	1
			Hazard-resistant structures and logistics facilities (EX_3)	0.0759	2
			Improved early warning and response system (EX_4)	0.0361	5
			Strategic planning for essential supplies shortage(EX_5)	0.0262	19
			Employee health protective clothing(EX_6)	0.0267	15
			Employee training and development program(EX_7)	0.032	9
Supply chain design (*SC*)	0.143	3	Use of Information technologies such as big data, blockchain and IoT (SC_1)	0.0256	22
			Facility location and distribution management(SC_2)	0.0357	6
			Inventory management (SC_3)	0.0267	15
			Suppliers' integration and collaboration (SC_4)	0.0321	8
			Business continuity plans(SC_5)	0.0231	24
Environmental (*EN*)	0.134	4	Green product design (EN_1)	0.0262	19
			Local environmental expertise(EN_2)	0.0273	14
			Reuse and recycling of packaging materials(EN_3)	0.0433	4
			Regular environmental auditing(EN_4)	0.0265	18
			Effective debris management(EN_5)	0.0205	27
Social (*SO*)	0.110	5	Membership of social networks (SO_1)	0.0285	12
			Safe work environment (SO_2)	0.0303	10
			Absence of asymmetric information (SO_3)	0.0267	15
			Improved brand image/ reputation (SO_4)	0.0208	25
			Improved cultural issues, e.g. improved local knowledge, low rate of corruption (SO_5)	0.0275	13
Economic (*EC*)	0.223	2	Efficient production methods (EC_1)	0.0261	21
			Effective time management/on-time delivery (EC_2)	0.0296	11
			Improved quality of products(EC_3)	0.0323	7
			Reduced operational costs (EC_4)	0.0623	3
			Economic recovery programs (EC_5)	0.0208	25

Note(s): Average cut of aspects = 0.2; Average cut of specific criteria = 0.037
Source(s): Table by authors

Table 8.
Final aggregated objective weights of the aspects and respective criteria for implementing SCS in the context of extreme weather events

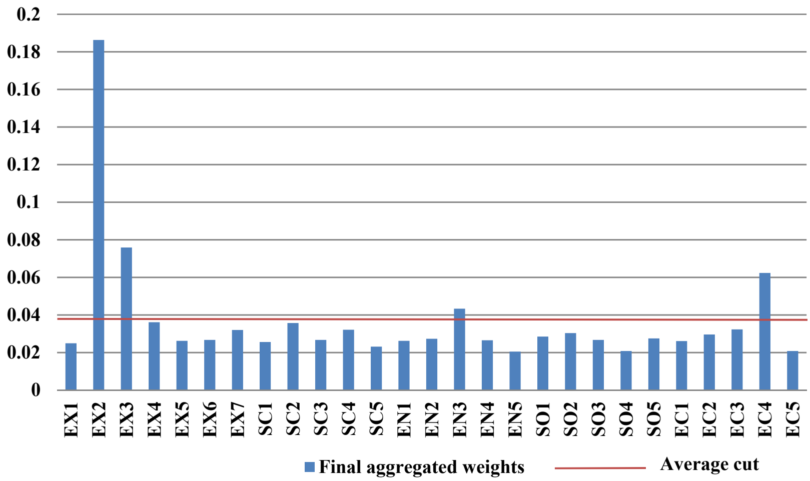


Source(s): Figure by authors

Figure 3. Final aggregated weights of the aspects

activities within the food and beverages manufacturing industry (Ikem, 2018; Ogbuchi, 2020; Woossen *et al.*, 2018). Besides, the Word Bank and the Food and Agricultural Organization has issued warning that extreme weather events will be on the rise in Nigeria and cause devastating impacts on the food and beverages manufacturing Industry (World Bank, 2016; FAO, 2017). Moreover, the high significance of the economic aspect, based on the results in this study, corroborates published studies on the critical role that economic criteria (e.g. budgetary allocations) play in implementing capital-intensive sustainability investments especially in emerging economies (Stevic *et al.*, 2020). Particularly, in Nigeria, eroded purchasing power as a result of the combined effect of inflation and exchange rate devaluation has forced manufacturing companies to place high considerations on the economic aspect for achieving SCS goals (Orji and Ojadi, 2021). Nevertheless, aspects such as environmental, social and supply chain have been ranked the least significant in this study problem. Yet still, it is recommended that the Nigerian food and beverage manufacturing firms make substantial efforts, to align their strategic operations with all the outlined aspects, for achieving increased sustainable performance values.

Going further, the average cut ($M = 0.037$) was utilized to reveal the specific criteria that has the potential to hedge against extreme weather events and minimize unsustainable trends in the supply chains of the food and beverages manufacturing sector. Figure 4 shows the final aggregated weights for the specific criteria considered in this study and the computed average cut. According to the study results in Figure 4, the highlighted most significant criteria include *efficient infrastructure system*, *well-designed hazard resistant structures*, *reduced operational costs* and *recycling of packaging materials*. This finding corroborates past published studies that suggest the importance of infrastructure systems (e.g. sustainable drainage systems) and well-designed hazard-resistant structures, as critical criteria for developing extreme weather preparedness, which is essential to overcome the negative impact of climate change (Adhikari *et al.*, 2020a; Papadopoulos *et al.*, 2016; Tchonkouang *et al.*, 2024). In Nigeria, there is poor investment in sustainable waste management systems and the improper application of the principles of the circular economy (Nwokolo *et al.*, 2023), resulting in unsustainable patterns within supply chains. For instance, the blockage of waterways via refuse dumping heightens flood occurrences in Nigeria and necessitates building sustainable drainage systems (Umar and Gray, 2023). Besides, there is need to integrate resilience in infrastructures such that these can provide normal operations as expected under climatic hazards. In essence, the study findings recommend developing effective climate change mitigation and adaptation policies to enable introducing sustainable



Source(s): Figure by authors

Figure 4.
Final aggregated weights and average cut of the specific criteria

drainage systems and designing hazard resistant structures to minimize the impacts of extreme weather and increase the sustainable performance of food supply chains (Sun *et al.*, 2024).

Going further, within the extreme weather preparedness aspect, the third ranked strategy is *improved early warning and response system*, followed by the *employee training and development*. This finding substantiates the need to utilize emerging digital technologies (e.g. artificial intelligence) to develop and improve early warning systems that can alert persons, including employees and managers in the Nigerian food industry of impeding disasters for effective evacuation plans (Jain *et al.*, 2023). Also, managers in the Nigerian food and beverages manufacturing industry can leverage past experiences to plan for future uncertainties, thereby enhancing sustainable patterns in their supply chains in the context of extreme weather events (Tchonkouang *et al.*, 2024). It is suggested that managers in the Nigerian manufacturing sector, collaborate with the government agencies to develop an approach to enable identifying potential threats from climate change and build a network to cater for their needs during weather hazards (Papaioannou *et al.*, 2020). Likewise, employee training programs are necessary to build the required skills for implementing sustainable criteria in manufacturing supply chains in the context of extreme weather events. This is in line with research evidence on the importance of capacity building via skills augmentation in managing climatic hazards, for sustaining the food supply chains in Nigeria (Vicente-Serrano *et al.*, 2012). *Employee health protective clothing* is the fifth ranked in this aspect. This result corroborates with research evidence on the need for employees in manufacturing firms to utilize protective clothing such as helmets, safety boots and cooling vests, for sustainable operations under climatic hazards (Samaniego-Rascon *et al.*, 2019). Besides, in 2024, the Nigerian Meteorological Agency (NiMet) issued a forecast warning on the prolonged heat-wave, advising citizens to wear protective clothing and avoid direct exposure in peak temperature periods (Elusoji, 2024). Moreover, the results shows that *strategic planning for essential supplies* and *adherence to climate change policies* are the least ranked within the extreme weather preparedness aspect.

Within the supply chain aspect, *facility location* ranks the most significant and this is followed by *suppliers' integration and collaboration*. This corroborates research evidence on the criticality of facility location in creating efficient and sustainable supply chains so as to account for the uncertainties and constraints inherent in the supply chain system (Tseng *et al.*, 2022). In developing countries like Nigeria, there is poor location of facilities for production, storage and waste collection, thus, leading to vulnerability to environmental hazards and unsustainable patterns in the supply chains of manufacturing firms (Fofou *et al.*, 2022). Besides, this is in line with past studies on the significant role of integrating suppliers and enforcing collaboration practices during a manufacturing firm's decision to implement sustainable supply chains in the context of extreme weather events (Nath *et al.*, 2020). In fact, collaboration among stakeholders in the food industry, including suppliers can facilitate the sharing of best practices, pooling of resources and creating solutions to enhance resilience and establish contingency plans for sustainability (Martindale *et al.*, 2023). Nigerian food supply chains need to intensify efforts to build relationships and collaboration for expected performance value (Adetoyinbo *et al.*, 2024). The next ranked within this aspect are *inventory management* and *use of information technologies* while the least ranked within the supply chain design is *business continuity*. Gloomily, in Nigeria, just like in most developing countries, there is still a lack of use of smart technologies to enhance decision-making for sustainability gains in supply chains. Thus, it is suggested to the decision makers in the Nigerian manufacturing sector to seek to adopt business continuity procedures to enable the identification of potential threats to SCS operations and their possible influences (Tseng *et al.*, 2022). Within the environmental aspect, *recycling of packaging materials* is the most significant and this is followed by *local environmental expertise*. There is research evidence that the reuse and recycling of packaging materials can increasing environmental performance and facilitate circular economy as well as minimize the impact of extreme weather events (Huysveld *et al.*, 2022). Also, according to a report by Insignia (https://insignia.ng/), the Nigerian food industry has made some progress by investing in recycling materials for packaging food products and acquiring energy-efficient technologies for sustainability goals in supply chains. However, the use of single-use plastic products as packaging materials in the Nigerian food and beverage industry remains a major cause of poor waste management resulting in floods and negating sustainable supply chain goals (Ayodele, 2021). Thus, we suggest to the Nigerian food industry to use biodegradable materials for packaging products. Moreover, it is necessary for managers and employees in Nigerian food manufacturing firms to acquire the skill set, knowledge and capabilities that are needed to reduce environmental degradation and hedge against extreme weather events. There is still a lack of technical skills and critical resources for climate change adaption and sustainability improvement in Nigeria and other African nations (Arthur *et al.*, 2024). The third ranked in the environmental aspect is *regular environmental auditing* and this is followed by *green product design*. In developing countries, like Nigeria, it is common to neglect environmental impact assessment of businesses, thus, heightening vulnerability to climate change and resulting in unsustainable patterns in supply chains (Ojiaka, 2024). Although, the least ranked in this aspect is *effective debris management*, it is suggested to Nigerian food manufacturers to ensure efficient waste management in order to minimize the negative impact of extreme weather events. This is because debris can clog drainage systems and cause flooding in vulnerable regions which invariably leads to unsustainable patterns in supply chains (Umar and Gray, 2023).

Within the social aspect, *safe work environment* is ranked the first and the second ranked is *membership of social networks*. In Nigeria, workers in industries are exposed health and safety risks linked to extreme weather events and require sustainable adaptive strategies like work safety standards for sustainable supply chains (Moda *et al.*, 2024). Besides, results corroborates with past studies that stress the importance of participating in business networks with common interests toward minimizing negative consequences of extreme weather events and achieving sustainability gains (Busch and Hansen, 2021).

The third ranked in this aspect is *improved cultural issues* and this is followed by *absence of asymmetric information*. Negative cultural issues like corrupt practices are prevalent in Nigerian businesses including food firms (Matemilola and Elegbede, 2017). Thus, there is need to emphasize local knowledge and develop a system to reduce corrupt practices, for reducing the negative environmental impact and improving sustainability. The least ranked in the social aspect is *improved brand image/reputation*. Within the economic aspect, the highest ranked strategy is *sufficient budget and reduced operational costs* and this is followed by *improved quality of products*. Most sustainable innovations have high initial investment costs, which require manufacturing firms to allocate sufficient budget to enable their successful adoption (Stevic *et al.*, 2020). The government agencies can also help in this context, by supporting Nigerian SMEs in the food sector with financial aid and subsidies for adopting sustainable innovations to hedge against climate hazards. Nevertheless, government funding for such sustainable projects is still low in Nigeria. Besides, the Nigerian food and beverage manufacturing firms can also integrate Lean Six Sigma to their business operations for reducing operational costs (Orji and U-Dominic, 2022). Moreover, there is need for the Nigerian food industry to utilize adequate storage facilities to minimize waste during climate hazards and thus, improve quality and ensure sustainable patterns in their supply chains (Haruna *et al.*, 2023). The third ranked in the economic aspect is *effective time management*. The last two criteria within the economic aspect are *efficient production methods* and *economic recovery programs*. Besides, the results suggest that the government agencies in Nigeria work synergistically with the food industry managers to propose government-assisted programs for economic recovery and sustainable development in the context of climate hazards (Ani and Boateng, 2024).

5.2 Study implications

This study undertook to examine the implications of extreme weather events through evaluating the aspects and criteria for implementing SCS in the context of extreme weather events. Some past published studies are available (Neri *et al.*, 2021; Orji and Ojadi, 2021), which provide theoretical sustainable supply chain management models. Nevertheless, the majority of these studies failed to address the implications of extreme weather events. In Nigeria, for instance, extreme weather events are prevalent and even projected to increase not only in intensity but also in frequency in the near future (NIMET, 2008). There are climate projections that indicate that there will be increased frequency of extreme rainfalls and heat waves in Nigeria (Elusoji, 2024). Consequently, the natural resources are susceptible to negative climate change impact. As well, the manufacturing firms face material shortage due to the climate disasters. Good enough, the Nigerian manufacturing firms, just like their counterparts around the globe, aspire to actualize sustainable supply chains, to meet stakeholders' requirements and reduce negative social and environmental consequences (Orji and Ojadi, 2021). Thus, this study posits that implementing sustainable supply chains in the context of extreme weather events is deemed to be multifaceted with aspects including extreme weather preparedness, supply chain design and the TBL (economic, environmental and social). Likewise, to facilitate the success of this venture, it is essential to evaluate the SCS from a multifaceted perspective.

Going further, most SCS studies have focused on developed economies and Asian emerging economies (Ikram *et al.*, 2021), while neglecting the African emerging economies. But our research has focused on an Africa emerging economy- Nigeria-to investigate the implications of extreme weather events. Another theoretical contribution of our research lies in the identification and subsequent evaluation of the degree of significance of the key aspects and specific criteria for implementing sustainable supply chains in the context of extreme weather events. Although, there are prior published studies that examine sustainable supply chain issues with focus on the manufacturing sector (Mani *et al.*, 2020; Orji and Liu, 2020; Tseng *et al.*, 2022), there is a scarcity of studies that have presented an adequate analysis of the specific criteria in the context of extreme weather events. In other words, there is a dearth of research that considers the implications of extreme weather events for SCS especially in the food and beverage manufacturing sector. Our study exists to fill this research gap, by identifying the criteria that are considered significant to successfully implement sustainable supply chains in food manufacturing firms, domiciled in Nigerian regions that are susceptible to extreme weather events. Hence, a structured integration of the findings of this study at the initial design-stage of sustainable supply chain systems will facilitate the building of a system that simultaneously hedges against the negative impact of weather conditions and improves sustainable performance.

From a managerial perspective, this research highlights the critical insights and implications that could encourage organizations to effectively coordinate their efforts for achieving sustainable supply chains under prevalent climate hazards. The results of our study show that the most significant aspects are related to “extreme weather preparedness” and “economic issues”. This implies that food manufacturing firms in areas vulnerable to extreme weather are not fully equipped in the current stage for implementing sustainable supply chains. Hence, creating a sequential plan to integrate the most significant aspects will invariably improve the success rate of adopting sustainable supply chain projects in the context of climate hazards. Consequently, these most significant aspects deserve the highest attention from decision makers. As climate hazards evolve, it will be necessary to increase investment in key adaptation strategies, possibly at the expense of efficiency (McKinsey Global Institute, 2020). The results also buttress the need for policy makers, managers and employees in the Nigerian food manufacturing industry to focus on short-term priority, the criteria which are the most significant. The highlighted most significant criteria include “efficient infrastructure systems (e.g. drainage systems)”, “well-designed hazard-resistant structures”, “reduced costs” and “recycling of packaging materials”. Correspondingly, the policy makers and administrators are expected to play a critical role in developing the required standards for implementing the emerging transition. In this context, the government agencies can assist food manufacturing managers through building efficient infrastructures such as sustainable drainage systems to mitigate floods. The government can also make efforts to provide financial aid to food firms in order to concretize their financial strength and support sufficient budgetary allocations for SCS under climate hazards. Likewise, the food and beverage organizations should consider designing hazard-resistant structures as well as introducing reuse and recycling of packaging materials for expected environmental improvements and onward transition to a circular economy. The successful integration of these most significant criteria will aid to pave pathways for the smooth implementation of sustainable supply chains and other technological innovations, toward increased competitive advantage.

Overall, the Nigerian business environment is vulnerable to climate hazards like floods, droughts, heat waves, etc. but under pressure to increase economic benefits while reducing environmental and social consequences. Besides, these climate hazards has led to disruption in the pattern of food production and distribution, further creating shortfall in supplies with rising prices and limited access to food products (Oyinloye *et al.*, 2018). And so now, the key issue for Nigerian manufacturing firms particularly in the food and beverage sector is how to simultaneously hedge against the negative impact of prevailing extreme weather conditions and improve sustainability in their supply chain networks. Hence, this research provides practical guidelines toward tackling this major issue.

6. Conclusion

Globally, there has been an unprecedented increase in the frequency and intensity of extreme weather events resulting in negative disruptions to organizational operations. In this context, manufacturing firms are expected to minimize the negative impact of extreme weather events in order to ensure the success of their strategic decisions especially the implementation of sustainable supply chains. However, the full-scale implementation of sustainable supply chains in the context climate hazards remains a distant dream in manufacturing organizations due to a lack of understanding on what can facilitate such a venture. As well, published studies on the topic are currently limited. To address the paucity in theory and practice, this study evaluates the aspects and criteria that can potentially facilitate implementing sustainable supply chains in the context of extreme weather events especially within the Nigerian manufacturing industry. Moreover, the Nigeria case is important, since Nigeria has been identified as one of the countries in the African region, that are most vulnerable to extreme weather events (Ani *et al.*, 2022; Climate Scorecard, 2019). Gloomily, the extreme weather events have led to devastating consequences to the food and beverages manufacturing sector in Nigeria (Ogbuchi, 2020). To that end, we introduced five aspects namely TBL (economic, social and environment) aspects in addition to the supply chain design and extreme preparedness aspects as relevant to the pursuit of achieving sustainable supply chains in the context of extreme weather events. Relevant criteria for facilitating sustainable supply chains in the context of extreme weather events were classified under these five aspects. In this regard, we finalized a total of twenty-seven criteria that were categorized under these five aspects for subsequent evaluation using a proposed model based on the BWM and entropy concept. Specifically, the BWM was applied to determine the subjective weights of the aspects and criteria based on the experts' preferential judgments while their final aggregated objective weights and degree of significance were determined using the entropy concept.

Based on the study results, the "extreme weather preparedness" and the "economic" aspect are the most significant to achieving sustainable supply chains under climate hazards in the Nigerian food and beverages manufacturing industry. This finding implies that the Nigerian food manufacturing industry in its current configuration is not fully equipped to effectively harness the potential of SCS, especially from the extreme weather perspective. The study results will presumably assist decision-makers in positioning viable niche regimes for SCS in the context of extreme weather events. As well, the study findings indicate that specific criteria such as "efficient infrastructure system", "well-designed hazard resistant structures", "reduced operational costs" and recycling of packaging materials' are the most significant to the success of sustainable supply chains under climate hazards in the Nigerian food industry. In this regard, it is suggested to government agencies and managers in the Nigerian food manufacturing industry collaborate toward designing a sequential pathway to aid in enforcing changes based on the most significant criteria derived from the study findings. Such required changes include investments in efficient infrastructure systems, designing hazard-resistant structures, providing financial subsidies and encouraging using recycled materials for packaging. Besides, managers in the Nigerian food and beverages industry can endeavor to implement Lean-Six Sigma practices to reduce costs and improve the quality of products. As well, it is suggested that managers utilize biodegradable materials for packaging products, to ensure sustainable waste management and prevent climate hazards like floods. This is particularly important since the use of plastic products for packaging in the Nigerian food and beverages industry contributes to blockage of waterways leading to floods and negative sustainable patterns in supply chains. Moreover, the general public in Nigeria should be educated on how to sort and separate waste packaging materials of food and beverage products, in order to ensure efficient recycling (Ibrahim *et al.*, 2023).

This study has certain limitations that do not deter the novelty of the research but rather present opportunities for further exploration and theorization of the study problem. The current study is focused on the Nigerian manufacturing sector and considers experts, with relevant levels of experience and managerial functions in the food and beverages firms that oversee the implementation of innovations such as sustainable supply chains. As such, the current study is geographically restricted. Another limitation of this study is that it employed a methodology based on integrating two MCDM methods, namely, BWM and entropy concept, to perform the analysis. As well, this study identified five aspects and twenty-seven criteria that can influence the success of sustainable supply chains under climate hazards in the food and beverages industry. The five aspects include the traditional TBL aspects/dimensions which include economic, environmental and social aspects as well as the supply chain and extreme weather preparedness aspects.

Based on these limitations, we suggest that future studies may provide a broader perspective of this study by considering experts not only in Nigeria but in other African nations and even Asian countries like China. Besides, experts from other industries such as the electronics industry and even the service industries like the logistics industries can be requested to participate in this study, in order to provide a broader scope of the study. The differences that may arise in the research results within the different industries would likely serve as a foundation to customize strategies to facilitate the growth of sustainable supply chains and hedge against extreme weather events. In addition, future studies may consider applying other MCDM methods like AHP, MULTIMOORA, DEMATEL, etc. or even adequately account for uncertainty in experts' judgments by integrating fuzzy sets in the proposed decision methodology. We believe that there is much scope to extend this research in other African nations and other countries that are prone to climate hazards. We also suggest that in the presence of large data sets, future studies may apply the structural equation modeling (SEM) technique to explore the most significant criteria for implementing sustainable supply chains in the context of extreme weather events. As well, a comparative analysis may be presented using the results from applying other models and the proposed methodology in this study. Also, future studies may consider identifying from a literature review additional aspects and criteria that may influence sustainable supply chains in the context of extreme weather events, in order to provide a broader perspective of this study. Moreover, future studies may consider reducing the aspects and specific criteria analyzed in this study, in order to provide a more concise perspective.

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