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# Climate Change Impacts' Mitigation Strategies in Sustainable Supply Chain Management and Pragmatism of Data Envelopment Analysis and Malmquist Index in its Measurement

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***Abstract*— The escalating consequences of climate change have highlighted the urgent necessity of integrating sustainability into supply chain management to mitigate environmental impacts while maintaining economic viability. This review systematically synthesizes the existing literature on mitigation strategies within Sustainable Supply Chain Management (hereafter: SSCM), with a focus on the practicality of analytical application of Data Envelopment Analysis (hereafter: DEA) and the Malmquist Index (hereafter: MI) in assessing eco-efficiency, productivity, and technological progress. Drawing upon an in-depth review of the literature conducted during the preparation of this article in February-March 2025, felicitous and expedient studies published from 1984 to 2024 were reviewed. It identified four principal mitigation pathways: the adoption of green technologies, carbon emission reduction initiatives, resource optimization through circular economy practices, and resilience enhancement against climate-induced disruptions. The integration of knowledge-based, systems, and swift-flow theories provides a robust conceptual foundation for understanding the dynamic and adaptive nature of SSCM. The findings indicate that technological innovation, digital transformation, and stakeholder collaboration are critical enablers of sustainable performance and climate resilience. Furthermore, the study emphasizes methodological advancements through the combined use of DEA and MI in benchmarking performance and tracking sustainability trajectories over time. Despite significant progress, notable gaps remain regarding the standardization of DEA models, the inclusion of social sustainability indicators, and the empirical validation of digitalization impacts. This review contributes to the theoretical and methodological advancement of SSCM by developing an integrative conceptual framework that links climate change impacts, mitigation strategies, and quantitative performance evaluation. The insights derived offer valuable guidance for researchers, practitioners, and policymakers seeking to design resilient, efficient, and environmentally responsible supply chains in an era of climate uncertainty.***

***Keywords*— Sustainable Supply Chain Management, Climate Change Impacts, Mitigation Strategies, Data Envelopment Analysis**

## I. INTRODUCTION

Sustainable Supply Chain Management (SSCM) stands at the intersection of environmental sustainability and efficient supply chain operations, increasingly confronting the challenges posed by climate change. Studies conducted by previous scholars have unearthed myriad instances regarding the adverse and detrimental impacts of climate change on various sectors such as agriculture, food security, water resources, and socioeconomic impacts (Adekanmbi et al., 2023; Bibi & Rahman, 2023; El-Rawy et al., 2023; Kaur, Singh, Maurya, Kumar, & Kumar, 2023; Newman & Noy, 2023; Turco et al., 2023). In order to ameliorate the aforementioned problematic situations, there are mitigation strategies in SSCM through which the deleterious effects of climate change can be alleviated, as implemented in former studies by scholars (Bai, Sarkis, Wei, & Koh, 2012; Chen, Sohal, & Prajogo, 2013; Dubey, Gunasekaran, & Papadopoulos, 2017; Feng et al., 2018; Gurtu & Johny, 2021; Luthra, Garg, & Haleem, 2013; Sarkis, 2020; Z. Zhang & Awasthi, 2014).

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Therefore, it can be deduced that the complexity of managing supply chains in a changing climate has been uncovered, highlighting the necessity of incorporating sustainable practices and technologies to mitigate adverse impacts.

It is worthwhile to mention that despite significant advancements in SSCM, there remain critical gaps, particularly in the integration of digital technologies and comprehensive risk management strategies. To address these, the research agenda should focus on exploring the role of digital technologies such as the Internet of Things (IoT) in enhancing SSCM efficiency and sustainability (Prajapati, Chan, Chelladurai, Lakshay, & Pratap, 2022). Consequently, investigating comprehensive risk management strategies that encompass supply, demand, and process risks to improve supply chain resilience and agility is essential (Chen et al., 2013; Gligor, Gligor, Holcomb, & Bozkurt, 2019). Assessing the impact of organizational culture on the adoption and effectiveness of SSCM practices is crucial, given its underexplored potential to drive or hinder sustainable initiatives (El Baz & Iddik, 2022; Sarkis, 2020). This focused research could pave the way for developing robust frameworks that integrate technology and culture into SSCM, ensuring resilience and sustainability in the face of emerging challenges.

In addition to previous notes and referencing the reviewed literature, which will be detailed in the literature section, there is a connection among Sustainable Supply Chain Management (SSCM), Data Envelopment Analysis (DEA), and the Malmquist Index (MI). This relationship will be explored in depth in the following sections of this study. To summarize, the effectiveness of DEA in benchmarking and improving supply chain sustainability is undeniable. DEA has shown versatility in assessing supply chain efficiency, identifying inefficiencies, and supporting strategic decision-making for enhancements. Furthermore, its application in forecasting and evaluating sustainable supply chain performance underscores its critical role in advancing SSCM practices. Similarly, the comprehensive applicability of the MI in measuring and analyzing changes in productivity and efficiency makes it an invaluable tool for researchers, policymakers, and industry practitioners aiming to enhance SSCM and overall sector performance.

Moreover, despite the extensive use of DEA in evaluating efficiency across various sectors, gaps remain in fully integrating DEA into SSCM (Fotova Čiković, Martinčević, & Lozić, 2022; Shabanpour, Yousefi, & Farzipoor Saen, 2021; Tajbakhsh & Hassini, 2015). Key research gaps and the suggested agenda include the development of a comprehensive framework that integrates DEA with sustainability dimensions (economic, environmental, social) specifically tailored for supply chain applications (Tajbakhsh & Hassini, 2015), and an investigation into the role of DEA in the selection of sustainable suppliers, considering the evolving importance of sustainability in supply chain decisions (Fotova Čiković et al., 2022).

An in-depth review of the literature identifies four main themes in mitigation strategies: (1) the adoption of green technologies and digital innovations, (2) the measurement and reduction of carbon emissions, (3) resource optimization based on circular economy principles, and (4) resilience building through risk management and stakeholder collaboration. These strategies are often evaluated using quantitative tools such as DEA and MI, which offer methodologies for benchmarking eco-efficiency, monitoring productivity changes, and recognizing technological advancements as drivers of sustainable performance. Together, these approaches create a cohesive framework that aligns environmental policy with operational excellence in supply chains.

Referring to the stated gaps, addressing these research needs will be crucial for building resilient, efficient, and sustainable supply chains capable of withstanding the challenges posed by climate change. Therefore, this study delves into how climate change affects supply chains, examines mitigation strategies through sustainable practices and technologies, and assesses the role of DEA and MI in enhancing supply chain efficiency and sustainability. The focus on DEA and MI offers insights into methodological advancements for evaluating and improving supply chain performance in the context of sustainability and climate resilience.

## II. Review of expedient literature

### *A. Climate Change Impacts Across Sectors*

Climate change poses unprecedented challenges across various sectors such as agriculture, food security, water resources, forest ecosystems, and socioeconomic structures, necessitating a reassessment of mitigation and adaptation strategies. This literature review surveys the current state of research on the impacts of climate change across various sectors, which will be highlighted in the following subsections.

#### Agricultural Impacts and Food Security

The reviewed literature collectively highlights the significant adverse impacts of climate change on agricultural productivity and food security, emphasizing the need for sustainable mitigation strategies. Bibi and Rahman (2023) provide a comprehensive overview of how climate change-induced abiotic stresses, such as salinity, drought, and temperature fluctuations, negatively affect crop productivity and soil health, proposing the use of biochar and biostimulants as mitigation strategies. Similarly, Adekanmbi et al. (2023) underscore the vulnerability of potato yields in Prince Edward Island, Canada, to climate change, predicting significant declines under various emission scenarios and suggesting the necessity of adaptive measures. Kaur et al. (2023) explores the exacerbated spread and severity of plant diseases due to climate change, indicating a need for interdisciplinary approaches to manage disease outbreaks effectively. Lastly, Neupane et al. (2022) review the impact of climate change on the yields of the world's top three cereals—wheat, maize, and rice—pointing out the potential of millets as a resilient alternative to traditional cereals. Together, these studies illustrate the multifaceted challenges posed by climate change to agriculture and food security, advocating for integrated, innovative, and sustainable approaches to ensure global food security.

#### Water Resources and Hydrological Changes

Climate change has a significant impact on water resources, leading to increased irrigation demands in arid regions and the acceleration of global flash drought occurrences. The study conducted by El-Rawy et al. (2023) highlights the projected rise in irrigation water requirements in Saudi Arabia's Al Qassim region as a result of climate change, foreseeing elevated evapotranspiration rates and increased water deficits for major crops under future scenarios. Moreover, Yuan et al. (2023) indicate a global trend toward more frequent flash droughts, emphasizing the difficulties posed by sudden-onset droughts to monitoring and forecasting endeavors. These research findings collectively stress the critical necessity for adaptive strategies in water resource management to alleviate the repercussions of climate change.

#### Ecosystem and Biodiversity Effects

The key findings from the reviewed papers indicate that anthropogenic climate change significantly exacerbates summer forest fires in California, affecting ecosystems and biodiversity. They stress that adaptive management strategies in forest ecosystems are crucial in mitigating climate change impacts, highlighting the importance of adopting sustainable practices and increasing resilience against climate change across different regions (Babić, Krstić, Vuković, & Kanjevac, 2023; Turco et al., 2023). The study by Turco et al. (2023) demonstrates that nearly all observed increases in burned area in California's summer forest fires over the past half-century are attributable to anthropogenic climate change. Additionally, Babić et al. (2023) emphasize the necessity of adaptive management in forest ecosystems, suggesting the implementation of measures such as supporting natural regeneration, cultivating mixed forests, and conserving genetic diversity to mitigate the impacts of climate change on ecosystems and biodiversity.

#### Socioeconomic Consequences

The socioeconomic consequences of climate change are profound and multifaceted, affecting economic growth, worsening vulnerabilities in low-income populations, and impacting household livelihoods, with a considerable portion of the costs attributed to extreme weather events. Newman and Noy (2023) quantify

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the global costs of extreme weather linked to climate change at $143 billion per year, emphasizing the substantial underestimation of economic impacts in prior models. This financial burden is primarily a result of human loss of life, highlighting the severe societal impacts beyond mere economic metrics.

Bartlett (2008) shifts the focus to children in lower-income countries, emphasizing their vulnerability and resilience. It argues that climate change affects children's health, safety, and long-term well-being, particularly in communities that are least equipped to adapt. This underscores the need for targeted interventions that consider the unique needs of younger populations.

The work by Byers et al. (2018) provides a comprehensive analysis of global exposure and vulnerability to climate change, indicating that exposure to multi-sector risks significantly increases with each degree of global mean temperature rise. Populations vulnerable to poverty face disproportionately higher risks, especially in Asian and African regions, which are predicted to bear the brunt of climate impacts. This analysis underscores the critical importance of sustainable development and poverty reduction in mitigating climate risk.

Lastly, Shen, Duan, Wang, and Zhang (2022) examine the vulnerability of household livelihoods to climate change in western China, identifying Ningxia as the most vulnerable region. This study emphasizes the role of local factors, such as the age of the household head and proximity to urban centers, in determining adaptive capacity, suggesting that localized strategies are essential for enhancing resilience.

Together, the aforementioned studies paint a comprehensive picture of the socioeconomic consequences of climate change, emphasizing the urgent need for targeted, region-specific interventions aimed at mitigating impacts and enhancing resilience across sectors and communities.

### *B. Climate Change Impacts on Supply Chain Management*

To begin with, it is worth mentioning that this section explores the impact of climate change on supply chain management, highlighting a consensus on the significant and diverse effects it has across various sectors. From agriculture and water resources to timber and broader industrial demands, climate change presents substantial risks. Studies emphasize the importance of implementing adaptive strategies in supply chain management to tackle challenges like reduced agricultural yields, higher irrigation needs, and increased forest fire risks stemming from human-induced climate change. The research underlines the essential requirement for supply chain operations to be resilient and adaptable to mitigate the negative effects of climate change on environmental resources and maintain sustainable supply chain continuity.

#### Environmental Impacts on Supply Chain Operations

The key findings from the reviewed papers suggest that climate change significantly impacts various environmental factors crucial for supply chain operations, including forest fires, agricultural productivity, water resources, and hydrology. Turco et al. (2023) highlight that nearly all observed increases in forest fire activity in California can be attributed to anthropogenic climate change, indicating risks to timber supply chains. Bibi and Rahman (2023) discuss the detrimental effects of climate change on agriculture, including soil degradation and reduced crop yields, posing threats to food supply chains. El-Rawy et al. (2023) find that climate change will increase irrigation water requirements in Saudi Arabia, impacting water availability for agriculture and related supply chains. Lastly, Palash et al. (2023) report that climate change affects the hydrology of the Brahmaputra River Basin, influencing water supply for various industries. These findings underscore the need for adaptive strategies in supply chain management to mitigate the impacts of climate change on environmental resources.

#### Economic Consequences of Climate Change in Supply Chains

The study by Adekanmbi et al. (2023) highlights significant projected declines in potato yields in Prince Edward Island (PEI), Canada, due to climate change, with implications for the agricultural supply chain. This research illustrates the necessity of climate adaptation strategies to mitigate the adverse effects of climate variability on agriculture, crucial for ensuring food security. In PEI, a key potato-producing region, the study

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employed the Decision Support System for Agrotechnology Transfer (DSSAT) potato model alongside Coupled Model Intercomparison Project Phase 6 (CMIP6) climate scenarios to project future yields. Findings indicate that, without intervention, potato yields could plummet by up to 80% by the 2090s under high-emission scenarios. Such dramatic declines underscore the economic consequences of climate change for supply chains, particularly in agriculture, where decreased production capacity could disrupt local and global markets, inflate prices, and exacerbate food insecurity. The study's emphasis on the need for adaptive measures, such as adjusting farming practices and implementing supplemental irrigation, points toward a broader imperative for supply chain resilience in the face of climate change. Table 1 contains a summary of relevant articles that deal with climate change and its multifaceted impacts across sectors, highlighting the need for research into the exploration of adaptive strategies and technologies that can mitigate the adverse impacts of climate change on supply chains, ensuring sustainability and resilience in the face of increasing climate variability.

Table 1: Summary of Relevant Articles Dealing with Climate Change and Its Multifaceted Impacts

| Authors | Research gaps | Main findings | Methodology | Measured variables | Future research |
|---|---|---|---|---|---|
| El-Rawy et al. (2023) | Not mentioned (the paper does not suggest any research gaps or unanswered questions) | Climate change will significantly increase irrigation water demands in Saudi Arabia's Al Quassim region, with higher deficits expected under the SSP5-8.5 scenario by 2100.<br>- Both temperature and rainfall are projected to rise, leading to increased evapotranspiration and irrigation needs.<br>- Adaptation strategies such as optimal irrigation planning and modern technologies are necessary to manage future water resource challenges. | Collecting current meteorological data from 13 stations in Saudi Arabia from 1991-2020<br>- Using 4 CMIP6 climate models to project future climate under SSP2-4.5 and SSP5-8.5 scenarios for 2040-2100<br>- Calculating reference evapotranspiration (ETo) and net irrigation water requirements (NIWR) using the FAO CROPWAT 8.0 model for the Al Quassim region | Not mentioned (the paper does not mention any measured variables) | Not mentioned (the paper does not suggest any explicit "future research" directions) |
| Palash et al. (2023) | 1. Lack of studies on the hydrology and water balance of Himalayan River basins, including the Brahmaputra River Basin.<br>2. Lack of studies quantifying the contribution of baseflow and snow/glacier melt to seasonal water yield, considering both high-altitude and low-altitude watersheds.<br>3. Lack of measured data, leading to the need for numerical modeling to study basin hydrology. | Snowmelt contributes significantly to the Brahmaputra's flow, but its contribution is projected to decrease by 17% annually due to climate change.<br>- The average annual water yield is projected to increase by 8%, with the most significant rise during the pre-monsoon season.<br>- The upper Brahmaputra will be most affected by climate change, necessitating adjustments in water management planning. | Developed a SWAT hydrological model for the Brahmaputra River Basin using publicly available global datasets for topography, land use, soil, and weather data<br>- Calibrated and validated the SWAT model against available measured and modeled streamflow data for tributaries in the basin<br>- Assessed the impact of climate change on the basin's hydrology using two greenhouse gas emission scenarios (RCP 4.5 and RCP 8.5) with four climate conditions projected for 2050 | Streamflow/discharge data from various river points and tributaries in the Brahmaputra basin | Not mentioned (the authors do not explicitly state any "future research" in the paper) |
| Neupane et al. (2022) | Not mentioned (the paper does not suggest any research gaps or unanswered questions that need further investigation) | Climate change poses a significant threat to the yields of wheat, maize, and rice due to rising temperatures and water scarcity.<br>- There is a need to increase cereal production by 70% by 2050 to meet global food demands despite decreasing arable land.<br>- Strategies to combat these challenges include using modern molecular techniques, agronomic practices, and | Use of the ARIMA model to generate simulated data for crop area and total production<br>Comparison of recent data (1999-2019) with future simulated data (2050-2070)<br>- Visualization of the data using GraphPad Prism software | Not mentioned (the paper does not report any empirically measured variables) | Not mentioned (the authors do not explicitly state any "future research" in this paper) |

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| | | cultivating climate-resilient crops like millets. | | | |
| Bibi and Rahman (2023) | Quantifying the reduced fraction of nitrous oxide or methane emissions from biochar application in different soil conditions<br>- Understanding the practical field-level impacts of bio stimulants and how external factors affect their performance<br>- Addressing policy and health/environmental concerns around large-scale biochar production and the release of black carbon particles | Climate change-induced abiotic stresses threaten global food security by affecting crop yields and soil properties.<br>- Biochar and bio stimulants are promising mitigation strategies that can improve soil health and crop resilience while reducing greenhouse gas emissions.<br>- Sustainable agricultural practices are necessary to counteract the negative impacts of chemical fertilizers and pesticides on climate change. | Not mentioned (the paper does not describe a specific methodology or experimental study) | Soil properties: texture, bulk density, organic matter content<br>Crop physiological responses and yield<br>Greenhouse gas emissions ($CO_2$, $N_2O$, $CH_4$)<br>Biochar carbon sequestration | 1. Mitigating the negative impacts of biochar on earthworm populations<br>2. Quantifying the reductions in nitrous oxide and methane emissions from biochar application in different soil conditions<br>3. Understanding the practical field-scale application of bio stimulants and the impact of external factors<br>4. Developing policies to address health hazards from black carbon particle release during large-scale biochar production |
| Adekanmbi et al. (2023) | - Lack of studies assessing climate change impacts on potato yields in Canadian provinces using the DSSAT model<br>- Lack of studies investigating the combined effects of temperature, $CO_2$, and precipitation on potato yields using the DSSAT model<br>- Lack of studies specifically assessing climate change impacts on potato yields in Prince Edward Island using the DSSAT model | - Future potato yields in PEI are projected to decline significantly under high-emission scenarios, with reductions of up to 80% by the 2090s.<br>- Even under low-emission scenarios, potato yields are expected to decline by 6-10%, indicating a need for adaptation strategies.<br>- The study provides a scientific basis for developing coping mechanisms to mitigate climate change impacts on potato yields in PEI. | - Collecting input data (weather, soil, crop management) for the DSSAT model<br>- Calibrating and validating the DSSAT model using experimental data on potato yields, planting/maturity dates, etc.<br>- Assessing the impacts of climate change on potato yields using CMIP6 climate data and the validated DSSAT model<br>- Considering 5 different greenhouse gas emission scenarios (SSPs) and 7 different global climate models (GCMs) to project future potato yields | - Daily precipitation<br>- Daily solar radiation<br>- Daily maximum temperature ($T_{max}$)<br>- Daily minimum temperature ($T_{min}$)<br>- Soil texture<br>- Soil organic carbon<br>- Soil drained upper limit<br>- Soil saturated water content<br>- Soil saturated hydraulic conductivity<br>- Soil root growth factor<br>- Soil lower limit<br>- Crop planting and maturity dates<br>- Tuber yields | Not mentioned (the authors do not explicitly state any specific future research directions in the paper) |
| Bartlett (2008) | - Lack of documentation on the specific risks faced by children and youth, and the factors supporting their resilience<br>- Lack of understanding on the impacts of climate change on older children and adolescents, including effects on education, employment, and migration | - Climate change disproportionately affects children, especially in lower-income countries, due to their increased vulnerability and developmental implications.<br>- Despite their vulnerability, children possess resilience and can actively contribute to addressing climate change challenges.<br>- There is a lack of disaggregated data on the specific impacts of climate change on children, complicating efforts to present a comprehensive picture. | Not mentioned (this paper does not describe a specific methodology, as it is a review article that synthesizes existing knowledge rather than presenting original research) | Not mentioned (the paper does not mention any measured variables) | 1) Documenting the specific risks faced by children and youth, as well as the factors supporting their resilience<br>2) Understanding how household survival strategies and caregiver mental health are affecting children<br>3) Examining the impacts of climate change on older children and youth, such as their education and employment opportunities<br>4) Directly engaging with children and youth to better understand their experiences and perspectives on the effects of climate change. |

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| Turco et al. (2023) | No research gaps are explicitly stated in the paper. However, the paper suggests that future research could explore the impacts of fire management policies, land use/cover changes, and incorporating fire processes into climate models, as well as ways to mitigate climate change impacts and improve forest resilience. | - Nearly all of the observed increase in burned area (BA) in California's forests over the past half-century is attributable to anthropogenic climate change.<br>- Historical model simulations show that anthropogenic forcing results in 172% more area burned than natural forcing alone.<br>- The signal of anthropogenic climate change on burned area was detected starting in 2001, with no detectable influence from natural forcing alone. | 1. Development of a climate-fire regression model using summer forest fire burned area (BA) as the dependent variable and climate variables (maximum temperature, precipitation, vapor pressure deficit) as predictors.<br><br>2. Use of climate model simulations from the DAMIP initiative, including both historical simulations with anthropogenic and natural forcings (CMIP6-ALL) and simulations with only natural forcings (CMIP6-NAT), to quantify the impact of anthropogenic climate change on forest fire BA.<br><br>3. Accounting for uncertainty from both the climate-fire model and the climate models by nesting the climate-fire model with an ensemble of climate model simulations and stochastic residuals. | 1. Burned area (BA) from the FRAP dataset<br>2. Monthly precipitation from the nClimGrid dataset<br>3. Monthly maximum temperature (TS MAX) from the nClimGrid dataset<br>4. Monthly mean vapor pressure deficit (VPD) calculated from the PRISM dataset | Not mentioned (the authors do not explicitly suggest specific lines of future research in this paper) |
| Kaur et al. (2023) | - Lack of data on the effects of elevated nitrous oxide and methane on plant disease factors<br>- Lack of information on the impacts of climate change on pollen transmission, vector reproduction, biological control, and cultural control measures<br>- Need for better understanding of the impact of drought and flooding on plant diseases<br>- Lack of research on how $CO_2$ affects plant infections by mollicutes, and lack of information on the effects of climate change on mite, nematode, and fungal vectors | - Climate change significantly affects the spread, multiplication, incidence, and severity of plant diseases, altering host-pathogen interactions and potentially leading to more severe disease epidemics.<br>- There is a critical need to update disease management procedures, develop resistant plant varieties, and adopt novel management approaches to ensure sustainable food production in a changing climate.<br>- Fungicide treatment and host-plant resistance are essential components of sustainable crop production systems and play a significant role in mitigating the impacts of climate change on agriculture. | Not mentioned (the paper does not describe a specific methodology or experimental study) | Not mentioned (the paper does not clearly mention any variables that were empirically measured as part of this study) | Not mentioned (the paper does not explicitly outline any specific "future research" directions, but it does highlight several areas where more research is needed to better understand the impacts of climate change on plant diseases) |
| Babić et al. (2023) | - Developing new forest management strategies and knowledge to adapt to changing environmental conditions, including new climate zones and forest ecosystems | - Climate change is causing significant stress on forest ecosystems due to increased temperatures, unbalanced precipitation, and extreme weather events.<br>- The primary cause of modern global | Not mentioned (the paper does not contain a distinct "methodology" section describing the specific methods used in this study) | Not mentioned (the paper does not appear to report any empirically measured variables) | Not mentioned (the paper does not contain any information or discussion about future research directions related to climate change and forests) |

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| | - Understanding how specific climate change impacts like increased temperatures and drought will affect different tree species<br>- Assessing the regional impacts of climate change on forests in the Western Balkans and other areas | warming is the increase in greenhouse gases, particularly carbon dioxide.<br>- Adaptive management strategies are essential to mitigate the impacts of climate change on forests, including increasing renewable energy production and energy efficiency. | | | |
| Newman and Noy (2023) | 1. Lack of geographical coverage of event attribution studies, with a bias towards high-income regions.<br>2. Uneven spread of research across different types of extreme weather events, with storms being underrepresented.<br>3. Differences in framing and methodological approaches in event attribution studies, which can lead to varying quantification of the role of anthropogenic emissions. | - The study estimates that US$ 143 billion per year of the costs of extreme weather events is attributable to climate change, with a significant portion due to human loss of life.<br>- Anthropogenic climate change accounts for 53% of the total economic damages recorded in the study's dataset.<br>- The total climate change-attributed costs of extreme weather over 2000-2019 are estimated to be US$ 2.86 trillion. | 1. Using the Extreme Event Attribution (EEA) methodology to quantify the causal link between anthropogenic greenhouse gas emissions and extreme weather events<br>2. Collecting data from available EEA studies and combining it with socio-economic cost data<br>3. Calculating the Fraction of Attributable Risk (FAR) to determine the portion of risk due to climate change<br>4. Extrapolating the results using a global average and regional average approach to estimate the global cost of climate change-attributed extreme weather events | 1. Direct economic damages from extreme weather events<br>2. Number of deaths from extreme weather events | 1) Improving the precision of their approach as more comprehensive EEA studies and economic cost data become available over time.<br>2) Expanding the geographical and event-type coverage of EEA studies to better align with human impacts.<br>3) Utilizing their attribution-based approach to provide evidence for climate change litigation efforts. |

*C. Mitigation Strategies in SSCM*

The collective insights from various studies demonstrate the importance of integrating green technologies, involving customers and technical requirements, adopting circular economy approaches, and enhancing resilience against climate risks. These strategies collectively contribute to reducing carbon emissions, optimizing resources, and ensuring supply chain sustainability and resilience, offering a multifaceted approach to addressing environmental challenges.

**Green Technology Adoption in Supply Chains**

Dubey, Gunasekaran, & Papadopoulos (2017) provide a comprehensive conceptual framework for Green Supply Chain Management (GSCM), emphasizing the significance of integrating knowledge-based view theory and systems theory to mitigate the adverse effects of climate change through sustainable supply chain practices. This framework lays a foundational theory for understanding the broader impact of GSCM on environmental sustainability.

Green Jr, Zelbst, Meacham, & Bhadauria (2012) provide empirical evidence on how GSCM practices enhance both environmental and economic performance in manufacturing organizations. Their findings suggest that collaboration with supply chain partners to improve environmental sustainability leads to better operational performance, underscoring the value of green technologies in supply chains.

Zhu, Geng, Fujita, & Hashimoto (2010) focus on the Japanese manufacturing context, revealing that internal environmental management is a critical GSCM practice. Japanese manufacturers have achieved significant environmental and financial performance improvements through GSCM, illustrating the effectiveness of green technologies in large industrial settings.

Luthra et al. (2013) identify and rank strategies for implementing GSCM in the Indian manufacturing industry. Their study emphasizes the significance of incorporating green technologies throughout supply chain stakeholders to improve operational performance, showcasing the broad geographical and sector-specific relevance of GSCM strategies.

Furthermore, Luthra, Garg, & Haleem (2015) delve into the critical success factors for achieving sustainability through GSCM in the Indian automobile sector. The study underscores the role of competitiveness as a driving force for the integration of green technologies in supply chains.

Feng et al. (2018) investigate the mediating role of operational and environmental performance between GSCM and financial performance. Their findings suggest that GSCM plays a crucial role in enhancing financial outcomes by improving environmental and operational efficiency, highlighting the economic advantages of adopting green technologies.

Y.-C. Huang & Huang (2022) explore the antecedents and consequences of sustainable GSCM, showcasing that awareness and pressure to engage in ecological modernization positively influence sustainability performance. This study underscores the strategic significance of green technologies in attaining comprehensive sustainability objectives.

Jiang, Han, & Huo (2020) examine the impact of IT use on GSCM, finding that IT for exploration and exploitation positively influences green strategy alignment and process coordination. This indicates the pivotal role of digital technologies in facilitating GSCM practices.

Lastly, El Baz & Iddik (2022) conducted a bibliometric analysis to explore the relationship between organizational culture and GSCM. Their findings suggest that organizational culture plays a crucial role in the successful implementation of GSCM practices, including the adoption of green technologies.

In summary, these studies collectively underscore the multifaceted benefits of integrating green technologies within supply chains, ranging from enhanced environmental and operational performance to improved financial outcomes and competitive advantage. The adoption of green technologies, facilitated by supportive organizational cultures and strategic IT use, is essential for the successful implementation of GSCM practices across different industries and regions.

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**Carbon Emission Reduction Strategies**

Z. Zhang & Awasthi (2014) introduce a sustainability function deployment (SFD) method to prioritize customer and technical requirements for sustainable supply chains, highlighting the importance of socio-economic-environmental perspectives in planning. Dey and Cheffi (2013) developed an analytical framework using the Analytic Hierarchy Process (AHP) to measure and benchmark the environmental performance of supply chains in manufacturing settings, focusing on strategic and operational decision levels. Bhattacharya et al. (2014) propose a fuzzy ANP-based balanced scorecard within a collaborative decision-making approach to measure green supply chain performance, emphasizing the role of eco-design and sustainable performance constructs. Collectively, these studies underscore the necessity of integrating multi-dimensional approaches ranging from customer involvement and benchmarking to collaborative frameworks for reducing carbon emissions in supply chain management.

**Resource Optimization and Circular Economy Approaches**

Gopal and Thakkar (2015) developed a composite sustainable supply chain performance index for the automobile industry, incorporating key sustainability indicators to enhance decision-making processes. Bai et al. (2012) introduced a method for assessing and selecting sustainable supply chain performance metrics, utilizing grey-based neighborhood rough set theory alongside the SCOR model. Cucchiella, D'Adamo, Gastaldi, & Koh (2014) underscored the benefits of GSCM through a practical examination of battery recycling, stressing the amalgamation of environmental and economic considerations via Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). Wadhwa (2014) explored the linkages between Quality Green, Environmental Management Systems (EMS), and lean practices in sustainable manufacturing among Small Medium Enterprises (SMEs). Finally, Bloemhof, van der Vorst, Bastl, & Allaoui (2015) provided insights into the sustainability evaluation of food chain logistics, demonstrating a proactive approach by food companies towards sustainability in response to market demands for eco-friendly products.

Through these studies, a narrative emerges that underscores the critical role of integrating and optimizing resources within supply chains to enhance sustainability. The emphasis on combining quantitative and qualitative measures, such as in (Gopal & Thakkar, 2015), the application of advanced theoretical frameworks to identify core sustainability measures as highlighted by (Bai et al., 2012), and the practical implications of GSCM practices in specific sectors discussed by (Cucchiella et al., 2014), collectively illustrate the multidimensional approach required for effective mitigation strategies in sustainable supply chain management. Furthermore, the observed market-driven shift towards sustainability in the food sector, as demonstrated by (Bloemhof et al., 2015), indicates a broader trend toward embracing circular economy principles, thereby reinforcing the importance of sustainable practices across industries.

**Resilience Building in Supply Chains Against Climate Risks**

Chen et al. (2013) highlight the significance of collaboration in supply chain risk mitigation, suggesting that supplier, customer, and internal collaborations are effective in reducing supply, demand, and process risks, respectively. This collaborative approach is crucial for enhancing resilience against climate-induced disruptions in supply chains.

Sarkis (2020) expands on the necessity of integrating sustainability and resilience in supply chain management, especially in light of the COVID-19 pandemic. The study calls for further research into the long-term sustainability impacts of such crises, implying that resilience against climate risks also requires a sustainability-focused approach.

Gurtu and Johny (2021) provide a comprehensive review of the literature on supply chain risk management, emphasizing the increasing uncertainties stemming from globalization and economic policies. Although not specifically targeting climate risks, the article highlights the importance of implementing efficient risk mitigation strategies that could be relevant to environmental challenges as well.

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Gligor et al. (2019) distinguish between agility and resilience in supply chains, identifying common dimensions such as flexibility, speed of operations, and environmental scanning. This differentiation is crucial for allocating resources efficiently towards building resilience against climate risks.

Finally, Dubey and Gunasekaran (2016) discuss the sustainable humanitarian supply chain design, emphasizing agility, adaptability, and alignment. These characteristics are crucial for humanitarian supply chains and are equally important for commercial supply chains confronting climate-related threats.

To conclude, the literature suggests that building resilience against climate risks in supply chains requires a multifaceted approach, incorporating collaboration, agility, adaptability, and a strong alignment with sustainability principles.

Table 2 contains a summary of the felicitous articles that deal with supply chain resilience and sustainability.

Table 2: Felicitous Studies Dealing with Supply Chain Resilience and Sustainability

| Authors | Research gaps | Main findings | Methodology | Measured variables | Future research |
|---|---|---|---|---|---|
| Chen et al. (2013) | - Inadequate research on comprehensive Supply Chain Risk Management (SCRM).<br>- Predominant focus on supply side risk, with less attention to demand and process risks.<br>- Lack of holistic studies considering supply chain risks as a whole.<br>- Insufficient empirical investigation into supply chain collaboration as a risk mitigation strategy. | - Process risk has the strongest direct negative effect on supply chain performance.<br>- Supply risk and demand risk also have significant negative effects on supply chain performance, with supply risk having a larger indirect effect through its impact on process risk.<br>- Supply chain collaboration, through information sharing and knowledge integration, can effectively mitigate different types of supply chain risks. | - 7-point Likert scale survey with respondents identifying a key product to reference<br>- Random sample of 2,500 manufacturing companies in Australia, with an 8.4% response rate (209 responses)<br>- Respondents were supply chain, production, or senior managers<br>- Confirmatory factor analysis was used to assess the measurement model | The measured variables in this study are supply risk, process risk, demand risk, supplier collaboration, internal collaboration, customer collaboration, and supply chain performance. | 1. Further research focusing on the "swiftness" component of the Theory of Swift, Even Flow<br>2. Exploring other perspectives of risk beyond the operational risk and variance-based view adopted in this study<br>3. Further conceptualization and operationalization of the knowledge-based view of supply chain advocated in this research |
| Sarkis (2020) | - Differences in supply chain responses to natural versus man-made crises.<br>- Impact of crises on supply chain and operations environmental sustainability performance during and after recovery.<br>- Insights from COVID-19 for local versus global supply chain crises and responses.<br>- Lessons from bullwhip events in crisis situations for management and waste in supply chains.<br>- Changes in lean effort perspectives due to COVID-19 and their impact on 'lean and green' supply chain outcomes.<br>- Whether agile supply chains are greener than lean supply chains.<br>- Impact of a broad-based organizational sustainability strategy on operations and supply chain practices and long-term sustainability outcomes. | - The COVID-19 pandemic has led to unprecedented events and responses in operations and supply chains, which require revisiting existing scholarly notions and ontology.<br>- Sustainability and resilience are complementary concepts that require joint investigation.<br>- The COVID-19 crisis may require adjustments to current theories or the development of new theoretical frameworks. | - Published literature<br>- The author's personal research experience<br>- Insights from virtual open forums<br>- Interviews with supply chain professionals and experts<br>- Emergent literature from practitioners, news sources, and academic sources (mostly opinion and exploratory research) | Not mentioned (the paper does not appear to report any empirically measured variables) | 1. Comparing the supply chain sustainability implications of natural disasters vs. man-made disasters<br>2. Investigating how the COVID-19 pandemic may impact post-crisis emissions and changes to sustainable supply chain policies, including environmental regulations<br>3. Conducting comparative analyses of the COVID-19 pandemic to other crises, both larger and smaller in scale, to understand how the environmental sustainability implications may differ |
| Gurtu and Johny (2021) | - Lack of risk managing strategies to understand the cause of disruption.<br>- Need for analytical models in SCRM.<br>- Need for quantitative modeling in SCRM. | - The authors conducted a comprehensive review of 455 SCRM journal articles published between 2010-2019, with a focus on 312 articles in ABDC-ranked journals.<br>- The authors also reviewed 143 articles published in non-ABDC journals to gain a broader understanding of SCRM risk factors.<br>- The authors conclude that their review | - Material collection: Searching the EBSCO premium database for peer-reviewed journal articles published between 2010-2019 that used the word "risk" in the title, keywords, or abstract<br>- Descriptive analysis: Analyzing the 455 articles found, classifying them into those published in ABDC-listed journals (312 articles) and non-ABDC journals (143 articles) | Not mentioned (the paper does not appear to report any empirically measured variables) | Not mentioned (the authors do not explicitly state any specific "future research" directions in this paper) |

| | | | | | |
|---|---|---|---|---|---|
| | | could help researchers conduct more detailed analyses on risk factors affecting supply chain networks, and that there is a need for greater focus on risk assessment, analysis, and management in global supply chains. | - Category selection: Further analyzing the ABDC-listed articles by journal ranking (A*, A, B, C)<br>- Material evaluation: Summarizing the key findings and research gaps in the literature | | |

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*D. Data Envelopment Analysis in Sustainable Supply Chain Management*

At this stage, it is worthwhile to demonstrate Data Envelopment Analysis (DEA)'s effectiveness in benchmarking and enhancing supply chain sustainability. DEA has proven to be a versatile tool in assessing the efficiency of supply chains, identifying inefficiencies, and facilitating strategic decision-making for improvement. Studies across different sectors, including manufacturing and renewable energy, have showcased DEA's capability to integrate environmental, economic, and social dimensions of sustainability. Furthermore, the application of DEA in forecasting and evaluating sustainable supply chain performance underlines its critical role in advancing Sustainable Supply Chain Management (SSCM) practices.

**Principles and Applications of DEA in Supply Chain Contexts**

The utilization of DEA in evaluating and enhancing supply chain efficiency emerges as a pivotal tool across various studies. Wong, Jaruphongsa, Lee, and Wong (2007) showcased DEA's application in measuring supply chain efficiency through Technical Efficiency (TE) and Cost Efficiency (CE) models, highlighting its potential to pinpoint and amend inefficiencies. Bowlin (1998) provided an introduction to DEA, emphasizing its capability to assess the efficiency of diverse entities without needing predetermined weights or explicit input-output relations, thus establishing its versatility in performance evaluation. Banker, Charnes, and Cooper (1984) delved into DEA's mathematical programming to evaluate management's past accomplishments, introducing methods to separate technical and scale inefficiencies, thereby enhancing DEA's utility as an evaluative tool. Cavaignac, Dumas, and Petiot (2021) applied a two-stage DEA to analyze the French Third-Party Logistics (3PLs) market, revealing low-efficiency levels but also highlighting the benefits of scale and specialization. Malhotra, Malhotra, and Lermack (2009) employed DEA to benchmark the financial performance of North American Class I freight railroads, illustrating DEA's effectiveness in identifying efficiency leaders and laggards within an industry. Lastly, H. Li, Jiang, Liu, and Su (2022) and Pham, Park, and Choi (2021) explored DEA's application in port logistics and container port efficiency, respectively, with the former using a four-stage model to assess Chinese coastal ports and the latter integrating DEA with fuzzy clustering to analyze top container ports worldwide, both underscoring DEA's adaptability in handling complex, uncertain data within the supply chain context (H. Li et al., 2022; Pham et al., 2021).

These studies collectively affirm DEA's critical role in supply chain management by providing a robust framework for efficiency evaluation, enabling the identification of inefficiencies, and facilitating strategic decision-making to enhance supply chain sustainability.

**Eco-efficiency Measurement Using DEA**

The study by Ng, Chuah, and King (2019) introduces an integrated approach that combines DEA with Life Cycle Assessment (LCA) to benchmark the environmental performance of production facilities. The research showcases how DEA can pinpoint the most efficient production facilities, enabling the comparison of environmental impacts among various production lines. This approach ultimately contributes to minimizing the overall environmental footprint during the manufacturing phase.

On the other hand, the study conducted by Curtis, Hanias, Kourtis, and Kourtis (2020) investigates the efficiency of wind farm companies by combining DEA with financial ratios. This research emphasizes the economic, environmental, and social dimensions of performance, demonstrating that DEA, supplemented with financial ratios, can effectively measure the economic efficiency of wind farms. This approach not only signifies the importance of economic efficiency in the renewable energy sector but also indirectly captures the environmental and social dimensions through its comprehensive analysis.

In conclusion, both studies highlight the versatility and comprehensive nature of DEA in evaluating eco-efficiency across various sectors of the supply chain, reaffirming its significance in sustainable supply chain management.

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**Benchmarking Sustainable Supply Chain Performance with DEA**

The application of DEA in SSCM emphasizes the increasing trend towards selecting sustainable partners using DEA methodologies, highlighting its efficacy and applicability in benchmarking SSCM (Fotova Čiković et al., 2022). Tajbakhsh and Hassini (2015) underscore the necessity for comprehensive performance measurements across sustainable supply chains, proposing a framework that integrates sustainability dimensions and operational decisions, thus facilitating practical performance benchmarking. Shabanpour et al. (2021) introduce a novel forecasting approach combining dynamic network DEA and artificial neural networks to evaluate and predict the sustainability of supply chains within a circular economy context, offering a new ranking approach based on sustainability trends and providing benchmarks for addressing potential future unsustainability.

Collectively, these studies illuminate the pivotal role of DEA in advancing SSCM through effective performance benchmarking and forecasting.

### *E. Malmquist Index in Sustainable Supply Chain Management and Its Practicality*

The Malmquist Index (MI) has been extensively applied across various sectors to measure productivity changes over time, highlighting its versatility and effectiveness in capturing both efficiency and technological shifts. From assessing the efficiency of China's digital economy (G. Zhang, Ye, & Sun, 2023) to analyzing the impact of demand shocks on Air Navigation Service Providers' (ANSPs) efficiency (Standfuss, Fichert, Hirte, & Fricke, 2023), and examining the competitiveness of commercial banks (Zhou, Yao, & Jiang, 2023), the MI's application ranges widely. It also extends to evaluating the performance of primary healthcare services (Capeletti, Amado, & Santos, 2024), comparing the productivity of Islamic banks in Indonesia and Malaysia (Uula, Rusydiana, & Ali, 2023), providing a broad overview of productivity changes in countries worldwide (Farnoudkia, 2023), and assessing the Total Factor Productivity (TFP) of the logistics industry (Y. Huang & Yang, 2023) and urban TFP in Hubei Province (Xu & Wang, 2023).

A consistent theme among these studies is the MI's capability to break down productivity into components stemming from efficiency changes and technological progress, offering detailed insights into the sources of productivity fluctuations. For instance, significant enhancements in China's digital economy efficiency were discovered mainly due to technological advancements (G. Zhang et al., 2023). Similarly, the improvement in the TFP of China's logistics industry was primarily attributed to technological progress (Y. Huang & Yang, 2023). In contrast, the "drag effect" of technological regression on TFP growth in Hubei Province was also highlighted by Xu and Wang (2023), emphasizing the MI's proficiency in pinpointing areas of concern.

Moreover, the MI analysis in Standfuss et al. (2023) revealed how external shocks, such as the COVID-19 pandemic, can lead to notable efficiency losses, showcasing the MI's utility in evaluating the resilience of sectors to unforeseen events. The study on Islamic banks by Uula et al. (2023) demonstrated the MI's application in the financial sector, revealing a relative outperformance of Indonesian Islamic banks over Malaysian ones. The global perspective provided by Farnoudkia (2023) further underscores the MI's adaptability in comparing productivity across diverse economic contexts and time frames, offering valuable insights for policymakers and stakeholders across different sectors.

Collectively, these studies underscore the MI's comprehensive applicability and utility in measuring and analyzing productivity and efficiency changes, making it an invaluable tool for researchers, policymakers, and industry practitioners aiming to enhance SSCM and overall sectoral performance.

### *F. Tracking Sustainability Improvements Over Time*

In the context of Sustainable Supply Chain Management (SSCM), tracking improvements over time through the Malmquist Index (MI) reveals varied efficiencies and productivity changes across different industries and regions. The MI, applied in diverse contexts from the citrus industry in Sichuan, China (He & Chen, 2023), to urban flood governance efficiency in Chinese provincial capitals (Guo, Hu, Li, & Zhang, 2023), indicates a

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general trend towards recognizing and attempting to quantify sustainability improvements. In Sichuan's citrus industry, the index highlighted inefficiencies caused by low technical efficiency and technological progress, alongside the impact of sustainable development policies (He & Chen, 2023). Similarly, the analysis of green development efficiency in Chinese oil and gas cities showed fluctuating efficiency levels, suggesting a need for increased green technology investment and regional synergistic development (Fei, Chongliang, Jie, Yana, & Haiyan, 2023). The green energy efficiency of countries along the "Belt and Road" initiative was found to be low, with significant regional differences, influenced by external factors like economic strength and R&D expenditure (S. Li, Wu, & Song, 2023). In the forestry sector, the MI identified reasonable resource allocation and rising operating efficiency, suggesting potential areas for policy focus (M. Li, Wang, Agyeman, Gao, & Sarfraz, 2023). Finally, urban flood governance was evaluated to have low average efficiency, highlighting scale efficiency as a constraint and the importance of adapting to annual precipitation variations (Guo et al., 2023). These findings from the aforementioned reviewed studies collectively underscore the utility of the MI in identifying areas for improvement and guiding policy in SSCM.

### *G. Assessing Technological Progress in Sustainable Supply Chains*

In the context of sustainable supply chains, understanding the role of technological progress is crucial. The study by H. Zhang, Shi, Jiang, Xu, and Shah (2023) demonstrates this within the domain of sports resource utilization across Chinese provinces. By employing a sophisticated methodology that includes the DEA-Slack Based Measure (DEA-SBM) and the Malmquist Productivity Index, the paper reveals a notable improvement in sports resource utilization efficiency driven primarily by technological advancements. This is a significant insight, as it underscores the potential of technological progress to enhance efficiency in the management of sports resources, which can be considered a part of broader supply chain management in the sports industry.

Likewise, Mahmoud, Zhang, Liu, and Zhu (2023) examine the operational efficiency of e-payment concept listed companies in China, focusing on technological progress using the DEA-MI model. The results show that, although operational efficiency is generally good, some companies need to enhance their technological capabilities to maintain or improve their market position. This reinforces the overarching idea that in sectors vital to sustainable supply chains, such as e-payment systems, technological innovation is essential for sustaining efficiency and competitiveness. Together, these studies offer compelling evidence that in the pursuit of Sustainable Supply Chain Management (SSCM), technological progress is a key driver of operational efficiency, regardless of the industry in focus.

### *H. Underlying Theories*

#### **Integration of Knowledge-Based and Systems Theories for Climate Mitigation**

The integration of knowledge-based view theory and systems theory offers practical approaches to mitigate climate change impacts. Knowledge management systems can enhance climate change mitigation performance (Sardjono, 2020) and support decision-making processes (Ahmed & Elshazly, 2021). A holistic framework combining indigenous knowledge systems with modern scientific methods can strengthen socio-ecological resilience (Chanza & Wit, 2016; Vadigi, 2016). Green Supply Chain Management (GSCM), grounded in knowledge-based theory, contributes to sustainable practices (Dubey et al., 2017). Multidisciplinary perspectives are crucial for building realistic predictive models and prioritizing mitigation measures, as stated by Nunes and Ferreira Dias (2022), in order to bridge the gap between theory and practice in reservoir management, as highlighted by Simonovic (1992), which are potentially applicable to climate change mitigation strategies.

#### **Swift Theory in Sustainable Supply Chain Management**

The concept of swift theory, particularly the Theory of Swift, Even Flow (TSEF), has been applied to improve process performance in supply chain management (Garn, 2015). TSEF can unify lean thinking with strategic vision, elevating lean to an enterprise-level approach (Garn, 2015). In the context of Sustainable Supply Chain Management (SSCM), swift theory contributes to integrating environmental, social, and economic criteria for long-term viability (Carter & Rogers, 2008). SSCM implementation frameworks can be categorized as reactive, cooperative, or dynamic models (Zimon, Tyan, & Sroufe, 2019). The practicality of SSCM is evident in its focus on reducing adverse impacts on the environment, society, and economy (Panigrahi, Bahinipati, & Jain, 2019). However, barriers to swift, even flow exist in internal supply chains, necessitating coordination between departments (Fredendall, Craig, Fowler, & Damali, 2009). A systems perspective can help integrate SSCM practices, potentially decreasing trade-offs and improving supply chain effectiveness (Vidal & Croom, 2018).

**Conceptual Roadmap**

Figure 1 illustrates an integrated framework that connects climate change impacts, mitigation strategies, and performance evaluation mechanisms within sustainable supply chains. The diagram highlights how environmental, economic, and social disruptions drive four primary mitigation strategies: green technology adoption, carbon reduction, resource optimization, and resilience collaboration. These strategies are evaluated using Data Envelopment Analysis (DEA) and the Malmquiest Index (MI) to benchmark eco-efficiency and monitor productivity changes. The color gradient from red to green signifies the transition from climate risk to sustainable performance and resilience.

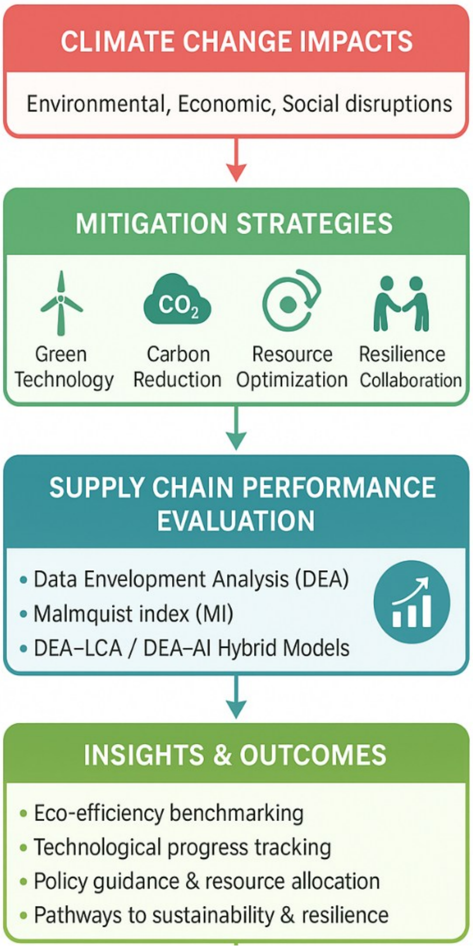


Figure 1: Conceptual Framework for Assessing Climate Change Mitigation and Supply Chain Performance (Source: Authors’ Elucidation of Existing Literature)

## III. Sources of data

We conducted a systematic exploration of mitigation strategies in Sustainable Supply Chain Management (SSCM) as a response to the impacts of climate change through Consensus and Elicit, without any filtering criteria, encompassing entire countries, full duration of the period, and including Q1-Q4 journals. A comprehensive literature search in Consensus and Elicit was performed in February-March 2025 across multiple databases, including Scopus, Web of Science, and Google Scholar, utilizing keywords such as "climate change," "mitigation strategies," and "sustainable supply chain management." The search results encompassed publications from 1984 to 2024 inclusive and resulting in identification of 1048 published articles in total through deep search strategy in Consensus and eligible ones were reviewed in this study to capture both foundational studies and recent advancements in the field. Studies were screened according to predefined inclusion criteria, which included relevance to SSCM practices, discussion of climate change mitigation, and peer-reviewed status. Conference abstracts, non-English publications, and studies unrelated to SSCM or mitigation strategies were excluded. Following the removal of duplicates, titles and abstracts were initially screened for relevance, and a full-text assessment of eligible studies was conducted. Both theoretical frameworks and empirical case studies were included to ensure a thorough understanding of mitigation strategies across diverse contexts. Data on mitigation approaches, frameworks, performance metrics, and case studies were extracted and synthesized to provide a comprehensive overview of strategies employed globally to enhance SSCM and mitigate the effects of climate change. This methodology facilitated the identification of emerging trends, gaps in the literature, and directions for future research.

## IV. Discussion

### A. *Synthesis of Key Findings*

This review systematically synthesizes the literature concerning the interplay between climate change, mitigation strategies, and Sustainable Supply Chain Management (SSCM). The findings indicate that climate change presents multidimensional risks across environmental, economic, and social domains. These risks encompass increasing instances of droughts and floods, disrupted production networks, rising input costs, and heightened vulnerability among marginalized populations. Collectively, these impacts have prompted a transition towards more sustainable, technology-driven, and resilient supply chain models. The reviewed studies identify four predominant themes in mitigation strategies: (1) the adoption of green technologies and digital innovations; (2) the measurement and reduction of carbon emissions; (3) resource optimization and the integration of circular economy principles; and (4) resilience building through effective risk management and stakeholder collaboration. These strategies are frequently assessed using quantitative tools such as Data Envelopment Analysis (DEA) and the Malmquist Index (MI), which provide rigorous methodologies for benchmarking eco-efficiency, tracking productivity changes, and identifying technological advancements as key drivers of sustainable performance. Collectively, these approaches establish a coherent methodological and conceptual framework that aligns environmental policy with operational excellence in supply chains.

### B. *Theoretical Implications*

This review highlights several significant theoretical insights.
First, the integration of knowledge-based theory and systems theory into Sustainable Supply Chain Management (SSCM) offers a robust conceptual framework for understanding how organizations learn, adapt, and co-evolve in response to climate challenges. Knowledge sharing—both internally and with external partners—emerges as a fundamental mechanism for disseminating sustainable practices and technologies. Systems thinking further elucidates how interconnected supply chain nodes influence one another in responding to external shocks, highlighting the importance of holistic, network-level mitigation strategies. Second, the role of technological progress is confirmed as a crucial factor influencing eco-

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efficiency. Decomposition results from the MI across multiple studies demonstrate that technological change, rather than efficiency improvement alone, is often the primary source of productivity growth. Therefore, investment in digitalization (e.g., IoT, blockchain, and advanced analytics) and clean technologies is not merely an operational decision—it is a strategic imperative for enhancing resilience and mitigating environmental externalities. Third, the evidence indicates a growing convergence between the concepts of sustainability and resilience. Traditionally regarded as distinct paradigms, recent literature emphasizes their complementarity: practices that enhance resilience (e.g., redundancy, agility, collaboration) also improve environmental and social performance. This integrated perspective calls for theoretical frameworks that adequately capture the dynamic trade-offs and synergies between these two domains.

### *C. Practical Implications for Managers and Policymakers*

From a managerial perspective, the findings support a data-driven, technology-enabled approach to sustainable supply chain governance. The principle of "measure to manage" is crucial: organizations should utilize DEA and MI models to identify efficiency gaps, compare performance among suppliers or facilities, and monitor sustainability progress over time. When integrated with Life Cycle Assessment (LCA) or carbon accounting, these tools facilitate detailed tracking of environmental and productivity trade-offs.

Strategic prioritization of technological investment is essential. Firms and policymakers must allocate resources toward digital infrastructures, green innovation, and renewable energy transitions, as these elements are fundamental to enhancing eco-efficiency. Additionally, resource optimization through circular economy practices—such as waste valorization, closed-loop logistics, and product life extension—significantly contributes to improving both environmental and economic outcomes.

Moreover, resilience should be institutionalized through collaboration. Multi-tier partnerships among suppliers, distributors, and customers can enable shared risk mitigation, joint research and development, and more flexible responses to climate-induced disruptions. Policymakers can enhance these initiatives by creating enabling environments through regulatory incentives, carbon pricing, and public-private partnerships that promote sustainable technology adoption and cross-sector collaboration.

### *D. Research Gaps and Future Directions*

Despite significant advancements, several research gaps remain:

1. Standardization of DEA frameworks: A unified framework that fully incorporates the triple bottom line (TBL) approach (economic, environmental, and social) in SSCM assessments is still lacking. Future research should define standardized input/output indicators, explore weight restrictions, and develop hybrid models that integrate DEA with econometric or machine learning approaches.
2. Technological heterogeneity: Malmquist analyses indicate that productivity and eco-efficiency gains differ by region and sector. Comparative studies are necessary to elucidate these variations, particularly in developing economies where technological diffusion is slower.
3. Empirical validation of digitalization effects: Although digital technologies are frequently proposed as enablers of sustainability, empirical quantification is limited. Field-based or longitudinal studies measuring the impacts of Internet of Things (IoT), blockchain, and Artificial Intelligence (AI) interventions would enhance understanding of causal relationships.
4. Integration of social sustainability:Social dimensions—such as labor welfare, equity, and community resilience—are often underrepresented in DEA and MI analyses. Developing appropriate indicators and integrating them into performance models should be prioritized.

Regional and event biases: Climate cost attribution studies tend to be disproportionately concentrated in high-income regions and major disaster events. Expanding geographical coverage will provide a more balanced global perspective on supply chain vulnerability.

## V. Conclusion

This review concludes that climate change presents systemic and interdependent risks to global supply chains while simultaneously catalyzing transformative opportunities for sustainable development. The convergence of green technology, resource circularity, carbon reduction initiatives, and collaborative resilience-building offers a comprehensive roadmap for organizations aiming to balance competitiveness with environmental stewardship. Quantitative methodologies—particularly Data Envelopment Analysis (DEA) and the Malmquist Index (MI)—have been essential in benchmarking eco-efficiency, analyzing productivity changes, and informing strategic investment decisions. However, methodological inconsistencies and the limited incorporation of social dimensions hinder their full potential. Addressing these limitations through integrative, standardized, and multidimensional DEA frameworks will significantly enhance evidence-based policymaking and managerial decision-making. From a practical perspective, the review emphasizes three key recommendations:

- For researchers: Develop integrative DEA-MI models that incorporate social indicators and test them across various industrial and regional contexts;
- For practitioners: Utilize technology adoption and benchmarking tools to align supply chain operations with sustainability objectives;
- For policymakers: Foster enabling conditions—such as funding for clean research and development, transparency standards, and incentives for a circular economy—that institutionalize sustainable supply chain practices.

Ultimately, the integration of methodological rigor with practical action represents the most promising pathway toward achieving climate-resilient, efficient, and equitable supply chains.

## VI. Contributions of the Review

### A. *Theoretical Contributions*

- Integrated Conceptualization: This paper synthesizes knowledge-based, systems, and swift-flow theories to elucidate the operation of Sustainable Supply Chain Management (SSCM) as a dynamic and adaptive system under climate stress;
- Framework Development: It presents a conceptual model that links climate impacts to mitigation strategies and performance evaluation Data Envelopment Analysis/Malmquiest Index (DEA/MI), thereby providing a structured foundation for future empirical research.

### B. *Methodological Contributions*

- Methodological Mapping: The review compiles and critiques existing applications of DEA and MI, identifying best practices and limitations, particularly the necessity for hybrid models Data Envelopment Analysis-Life Cycle Assessment, Data Envelopment Analysis-Artificial Intelligence (DEA-LCA, DEA-AI) and the inclusion of social indicators;
- Quantitative Advancement: It emphasizes how Malmquist decomposition clarifies the distinction between technological change and efficiency improvement, establishing a basis for evaluating innovation-driven sustainability transitions.

### C. *Practical Contributions*

- Actionable Managerial Insights: The findings are translated into practical applications, such as DEA-based supplier benchmarking, carbon performance monitoring, and prioritization of technology-driven circular models;

- Policy Guidance: The review identifies sectoral and geographic gaps, offering direction to policymakers for targeted incentives, research funding, and global data harmonization.

*D. Research Agenda*

- Develop a standardized DEA-MI framework that encompasses economic, environmental, and social indicators;
- Conduct empirical field tests on digital and IoT interventions and their measurable impact on eco-efficiency;
- Expand comparative Malmquist studies across different income groups and industries to identify dynamics of technology diffusion;
- Integrate life cycle analysis with DEA benchmarking for a comprehensive performance evaluation.
- These contributions enhance both the theoretical and practical understanding of how supply chains can transition toward sustainable and climate-resilient futures.

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## Strategije za blažitev vplivov podnebnih sprememb v trajnostnem upravljanju oskrbovalne verige in pragmatičnost analize podatkovnega ovijanja in Malmquistovega indeksa pri njenem merjenju

**Izvleček** – Posledice podnebnih sprememb so poudarile nujno potrebo po vključitvi trajnosti v upravljanje oskrbovalne verige, da se zmanjšajo vplivi na okolje in hkrati ohrani gospodarska uspešnost. Pregled sistematično združuje obstoječo literaturo o strategijah blaženja v okviru trajnostnega upravljanja oskrbovalne verige, s poudarkom na praktičnosti uporabe analize podatkovnega ovijanja in Malmquistovega indeksa pri ocenjevanju ekološke učinkovitosti, produktivnosti in tehnološkega napredka. Na podlagi poglobljenega pregleda literature, opravljenega med pripravo tega članka v februarju in marcu 2025, so bile pregledane ustrezne in primerne študije, objavljene med letoma 1984 in 2024. Opredeljene so bile štiri glavne poti za ublažitev: sprejetje zelenih tehnologij, pobude za zmanjšanje emisij ogljika, optimizacija virov s praksami krožnega gospodarstva in povečanje odpornosti proti motnjam, ki jih povzročajo podnebne spremembe. Integracija teorij, temelječih na znanju, sistemih in hitrem pretoku, zagotavlja trdno konceptualno podlago za razumevanje dinamične in prilagodljive narave upravljanja trajnostnih oskrbovalnih verig. Ugotovitve kažejo, da so tehnološke inovacije, digitalna transformacija in sodelovanje zainteresiranih strani ključni dejavniki za trajnostno delovanje in odpornost na podnebne spremembe. Poleg tega študija poudarja metodološke napredke z združeno uporabo analize podatkovnega ovijanja in Malmquistovega indeksa pri primerjalni analizi uspešnosti in spremljanju trajnostnih potekov v času. Kljub znatnemu napredku ostajajo opazne vrzeli v zvezi s standardizacijo modelov analize podatkovnega ovijanja, vključitvijo kazalnikov socialne trajnosti in empirično validacijo vplivov digitalizacije. Ta pregled prispeva k teoretičnemu in metodološkemu napredku upravljanja trajnostnih oskrbovalnih verig z razvojem integrativnega konceptualnega okvira, ki povezuje vplive podnebnih sprememb, strategije blaženja in kvantitativno ocenjevanje uspešnosti. Pridobljena spoznanja ponujajo dragocene smernice za raziskovalce, strokovnjake in oblikovalce politik, ki si prizadevajo oblikovati odporne, učinkovite in okolju prijazne oskrbovalne verige v času podnebne negotovosti.

**Ključne besede** – trajnostno upravljanje oskrbovalne verige, vplivi podnebnih sprememb, strategije blaženja, analiza podatkovnega ovijanja

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