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Contents

Environmental Resilience: Transition to regenerative supply chain management

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A B S T R A C T

Global supply chains face mounting pressures for sustainability, necessitating a shift from Green Supply Chain Management (GSCM) towards Regenerative Supply Chain Management (RSCM) to address environmental concerns and enhance Resilience. This transition addresses environmental concerns while improving and supporting Resilience within supply networks. My aims were twofold: (1) To assess the resilience-enhancing mechanisms during the transition to RSCM through a comprehensive review process, and (2) to uncover critical factors and themes of the RSCM. The study employed qualitative interviews as the primary method to collect data using a structured questionnaire. The study adopted snowball sampling based on the referral and recommendation of the respondents. The study investigated vital strategies and challenges for adopting RSCM, explicitly focusing on environmental sustainability. The results indicated that the transition emphasizes a shift from harm reduction to ecosystem restoration, highlighting the importance of environmental restoration in RSCM. Additionally, RSCM places a pronounced emphasis on resilience-building strategies compared to GSCM, underscoring the need for more comprehensive integration of Resilience within supply chains during this transition, particularly in an environmental context. I also developed a framework illustrating the transition from GSCM to RSCM, emphasizing environmental considerations. Additionally, this study contributes novel insights into the dynamic landscape of sustainable supply chain management, emphasizing the importance of resilience-building strategies, particularly in an environmental context, during the shift to RSCM.

Keywords: Regenerative Supply Chain Management; Green Supply Chain Management; resilience enhancing mechanisms; Environmental Resilience

1. Introduction

Regenerative Supply Chain Management (RSCM) has revolutionized sustainability practices within the broader supply chain management framework. It stems from acknowledging merely minimizing negative impacts (as in green supply chains). More is needed; the focus shifts toward actively restoring and enhancing ecosystems and environmental upgrades while conducting business operations [1,2]. The term "regenerative" emphasizes replenishing natural resources, enhancing biodiversity, and fostering ecosystems' Resilience. It seeks to go beyond reducing harm to improvingenvironmental and social conditions [3–5]. The concept of regenerative practices draws inspiration from various disciplines, including ecology, biology, and sustainable development. It aligns with circular economy principles, biomimicry, and cradle-to-cradle design [6,7].

Rooted in understanding natural systems, regenerative supply chain management aims to mimic nature's processes, emphasizing closed-loop systems, renewable energy sources, waste reduction, the utilization of sustainable materials, and pro-environmental practices [8,9]. This approach views supply chains as integral parts of larger ecosystems and envisions businesses as catalysts for positive environmental and social change. The study focuses on the transformative shift from green supply chain management to regenerative supply chain practices through resilience-enhancing mechanisms [10–12]. Additionally, the study aimed to analyze the theoretical underpinnings and practical implications of this paradigm shift in the context of modern business operations. So, itexplores how companies are transitioning towards regenerative practices, their challenges, and the potential benefits for businesses, the environment, and society at large [11,13].

Existing literature on regenerative supply chain management needs a cohesive integration of the 'Resilience-Enhancing Mechanisms' construct within the framework [14–16]. Prior studies have emphasized the significance of Resilience in sustainable supply chains; however, they have yet to sufficiently explore its specific role and influence in transitioning from GSCM to RSCM [14,17]. In the same way, theoretical recommendations from past research highlight the crucial need to delineate and examine how resilience-enhancing mechanisms, such as adaptive capacity, robustness, and flexibility, interact within the framework of RSCM strategies [18,19]. Similarly, [17,20] recommends that the understanding and influence of these mechanisms on the successful implementation of regenerative practices still needs to be explored, creating a distinct theoretical gap that requires focused investigation. Addressing this gap is vital to establishing a comprehensive theoretical foundation, providing businesses with actionable insights into fostering Resilience within their supply chains while adopting regenerative strategies [20–22].

Based on the above-cited literature, the study explores the question, "How can organizations enhance environmental Resilience during the transition to regenerative supply chain management?Thus, I aim to investigate RSCM to enhance Resilience within supply chains and facilitate sustainable business practices. Specifically, the study aims to explore the transition from GSCM principles and identify strategies to optimize RSCM practices, focusing on fostering Resilience, mitigating challenges, and maximizing benefits within contemporary business operations.

The study contributed to the existing body of knowledge in RSCM and its distinctive contribution to addressing a specific theoretical gap. Previous research has highlighted the importance of Resilience in sustainable supply chains; however, the study focuses on the integration of 'Resilience-Enhancing Mechanisms' within the RSCM framework. This targeted exploration provides a novel perspective on the transition from GSCM to RSCM, offering insights beyond the current theoretical landscape. Thus, the study contributes to advancing sustainable and resilient business practices by providing a nuanced understanding of how adaptive capacity, robustness, and flexibility interact within the context of RSCM.

The paper is structured as follows: Initially, it maintains an introduction and gaps followed by a comprehensive literature and theoretical review. In the third section, a detailed methodology for the study is given. In the subsequent section, findings from the interviews are mentioned in narrative and thematic form, followed by a discussion, conclusion, and recommendations.

2. Literature review

Fostering Resilience within supply chains through optimizing RSCM while transitioning from GSCM principles is multifaceted [6,23]. RSCM's optimization for resilience enhancement involves several interconnected elements and strategies, primarily focusing on reshaping supply chain processes, emphasizing adaptive capacities, enhancing robustness, and fostering flexibility [14,24].

First, optimizing RSCM requires a fundamental reconfiguration of supply chain processes. This encompasses integrating closed-loop systems, which emulate natural processes, facilitating waste reduction and resource efficiency [25]. It is natural that when loops are closed in the supply chain processes, the process will upgrade and minimize the waste. It also helps develop sustainable materials and encourages the reuse and recycling of the material. These practices bolster Resilience in supply chain processes to external disruption and ensure a reliable energy supply chain against energy disrupted supply [26,27]. At the same time, these processes and practices reconfigure renewable energy resources and sustainable practices, reducing wastage and environmental footprint [28,29].

Secondly, adaptive capacity practices must be incorporated to foster Resilience in supply chains. It involves developing a mechanism to respond to unforeseen contingencies and disruption [7,30]. Similarly, agile and flexible structures must be implemented to reconfigure and respond to market changes (supply and demand), natural disasters, and any other contingencies, emergencies, or crises. However, it needs strategic partnerships, advanced technology, and diversified sources [31]. Likewise, advanced data analytics can process accurate data and respond accordingly to changing structures [32,33].

Additionally, for the optimization of the RSCM and bolstering Resilience, there is a need to improve the robustness of supply chain management processes [22]. Robustness is the ability to reduce disturbance and manage all the operations most desirably. It focuses more on eliminating interruptions. To come up with robustness and optimization, the companies need to bring drastic changes in the process and develop a better mechanism, which should have, but not be limited to, backup plans, buffer zones, or safety stocks to accommodate disruption. Moreover, it involves constantly evaluating and minimizing vulnerabilities [34,35]. Reduction in dependencies on a single/sole source, marker, supplier, and region can affect the robustness of the supply chain processes. In the same way, implementing risk management strategies can enhance robustness and add to the resilience mechanism in RSCM [36,37].

Last, flexibility in RSCH processes emerges as a critical element in enhancing or optimizing RSCM for Resilience in the supply chain. Flexibility enhancesthe processes from an inside perspective and develops a responsive mechanism for changing market, environmental, and regulatory conditions without compromising efficiency [15,38]. A range of flexibility strategies, like modular design, can easily configure products and processes and contribute to innovation and continuous improvement [31,39].

The above-cited debate confirms that multifaceted mechanisms are needed to increase Resilience in RSCM. It can minimize disruption and its associated impacts [40]. At the same time, it increases sustainability and competitive advantage in volatile markets [36,41]. Moreover, businesses need to be aligned with sustainable business practices so that companies can positively contribute to environmental preservation, social responsibility, and long-term economic validity [42,43]

In a nutshell, the literature proclaims that optimizing the implementation of RSCM to foster Resilience within supply chains while transitioning from GSCM principles necessitates a holistic approach. It involves reconfiguring supply chain processes, emphasizing adaptive capacities, enhancing robustness, and fostering flexibility. The outcomes of this optimization extend beyond mitigating disruptions, encompassing sustainability and competitive advantage while contributing to environmental and social well-being. Table 1 compares GSCM and RSCM based on the literature cited above.

Table 1. Comparison of GSCM and RSCM.

Items	GSCM	RSCM
Focus	Minimize negative environmental impacts	Actively restore and enhance ecosystems
Objective	Reduce harm to the environment	Improve environmental and social conditions
Inspiration	Sustainability and eco-efficiency	Principles of circular economy, biomimicry, and cradle-to-cradle design
Approach	Emphasizes reducing waste and emissions	Mimics nature's processes, closed-loop systems, renewable energy, sustainable materials
View of Supply Chains	As separate entities from ecosystems	Integral parts of larger ecosystems
Business Role	Mitigating environmental impact	Catalyst for positive environmental and social change
Strategy	Focus on sustainable sourcing and production	Closed-loop systems, waste reduction, sustainable materials
Goals	Decrease environmental footprint	Enhance biodiversity, replenish natural resources
Fundamental Principle	Eco-efficiency and waste reduction	Restoration, Resilience, and improvement of ecosystems
Long-term Vision	Environmental sustainability	Environmental and social improvement

3. New perspective of the RSCM

RSCM represents a paradigm shift from traditional supply chain models, aspiring to sustain and rejuvenate ecosystems. Central to RSCM is adopting a systemic thinking approach, acknowledging supply chains as interconnected components within broader socio-ecological systems [44]. This transformative perspective underscores the importance of Resilience in addressing systemic challenges, enabling organizations to navigate complexities and uncertainties more effectively [12,45]. Moreover, RSCM has its roots in nature's design principles. It employs biomimicry to create closedloop supply chains to minimize waste and optimize resource utilization. By incorporating nature's modularity, diversity, and adaptability strategies, RSCM enhances sustainability and fosters innovation and efficiency [46]. At the same time, RSCM goes beyond operational practices to embrace regenerative business models and prioritize long-term sustainability and collaboration among stakeholders. It also encourages inclusive societies and promotes fair labour practices. These RSCMpractices contribute to building resilient communities capable of surviving socio-economic challenges [47–49].

Furthermore, RSCM recommends diversification, flexibility, and scenario planning to ensure business continuity in the face of disruptions [50]. Last, RSCM develops comprehensive metrics to evaluate frameworks and assess ecological, social, and economic indicators. These indicators giveorganizations insights to drive continuous improvement and regenerate supply chain sustainability [51]. Its synthesis is presented in Table 2.

Table 2. Emerging aspects of RSCM.

Aspects of RSCM	Description
Transformative Approach	RSCM transcends traditional supply chain models, aiming to restore ecosystems sustainably. It adopts a system thinking approach, fostering Resilience to systemic challenges.
Nature's Design Principles	RSCM leverages biomimicry to create closed-loop supply chains, minimizing waste and maximizing resource use.
Regenerative Business Models	RSCM prioritizes long-term sustainability and collaboration across stakeholders, fostering inclusive societies.
Resilience and Risk Management	RSCM emphasizes diversification, flexibility, and scenario planning to ensure business continuity.
Social Equity and Inclusive Value Chains	RSCM promotes fair labour practices and economic prosperity, contributing to resilient societies.
Metrics and Evaluation Frameworks	RSCM advocates for comprehensive metrics assessing ecological, social, and economic indicators.
Transformative Approach	RSCM transcends traditional supply chain models, aiming to restore ecosystems sustainably. It adopts a system thinking approach, fostering Resilience to systemic challenges.

4. Theoretical support of the study

There are many theories related to the study. The study incorporated the resilience theory, complex adaptive systems theory, and transition management theory in detail and later presented its synthesis in the context.

4.1. Resilience theory (RT)

RT is more to the core context of supply chain management. It explores the capacity of supply chains to withstand and recover from disturbances while maintaining functionality [52,53]. It originates from various disciplines, including ecology, psychology, and engineering, and focuses on understanding how systems can absorb disturbances, adapt to change, and maintain their functions and structures [28,54]. Initially developed in ecological sciences, resilience theory gained traction for its applicability in various complex systems, including supply chains. It has evolved and has been widely adopted in fields concerned with managing complex systems [41,55]

It emphasizes the need to design and manage supply chains that can adapt swiftly to disruptions, ranging from environmental changes to economic shifts or unexpected natural disasters [36].Resilience theory suggests that by integrating flexibility and learning mechanisms into supply chain strategies, organizations can enhance their ability to respond effectively to unforeseen challenges, minimize disruptions, and maintain operational continuity [56,57].

One of the main focuses of resilience theory is to increase the systems' capacity to face challenges and disruption. It absorbs shocks and recovers quickly after disturbances [28]. Moreover, it proposes to develop and adopt a robust system to manage and mitigate risks and uncertainties[12,58]. It involves understanding for both, i.e., responding to predictable changes and unexpected events. These eventsmay vary in intensity; however, through developing robust mechanisms, uncertainties like natural disasters, market fluctuations, or disruptions in the supply chain can be handled in the best possible and optimal ways [15,54].

Various mechanisms can help develop Resilience from a supply chain perspective. It starts with developing redundancies and making backup plans to handle unexpected and unwanted situations. Similarly, flexibility should be incorporated into the system, and alternatives should be considered to handle the disruption [7]. This leads to a diversity of resources, processes, and transportation, reducing risks and enhancing Resilience [59]. This principle is logical and natural in that diversifying the

resources, processes, methods, and models reduces the risk and enhances Resilience [7,12,54].
At the same time, resilience theory also looks for learning and adaptability. Through active monitoring, assessing, and analyzing, another crucial aspect of resilience theory in supply chains is the ability to learn and adapt. This involves monitoring, analyzing, and learning from past disruptions to improve future responses [34]. It includes developing capabilities for rapid decision-making and response during crises and fostering a culture of continuous improvement and innovation within supply chain operations [39]. Resilience theory supports reducing negative impacts and enhancing supply chains' adaptive capacity [13].

4.2. Complex adaptive systems theory (CAST)

CAST focuses on understanding how complex and interconnected systems of supply chain management work as a dynamic entity to respond to complex situations. At the same time, it also ensures the system can self-organize itself in response to disruption [16,39]. Moreover, it exhibitsemergent behaviours and recognizes supply chains as networks comprising interconnected agents, processes, and interactions. CAST also highlights that all these systems operate well-connectedly, where small process changes can lead to significant changes in some other processes or products [60].
Moreover, this CAST also recognizes the importance of the decentralized nature of the supply chain. All individual entities should be able to adjust their behaviours according to the changing circumstances [52,61]. At the same time, it provides a framework to understand how supply chains dynamically evolve and how they self-organize and innovate in response to the shift toward regenerative practices[11,15,62]. Consequently, these practices of emergent behaviours, feedback loopmechanisms, and decentralized decision-making shape supply chains' ability to enhance Resilience during the transition phase [19,52,63].

4.3. Transition management theory (TMT)

As the name indicates, the theory's core is to manage and facilitate the transition from one state to another [64]. In the field of supply chain management, it provides a comprehensive framework and guidelines for the change of processes from one state to another [7,65]. It recommends deploying better and flexible governing mechanisms and flexible and adaptive strategies, and it seeks the involvement of all stakeholders to effectively transition from one process to a better-optimized one [33]. This theory acknowledges the involvement of multiple factors and actors in the transition process, with some support and some negation. However, it recommends starting with optimal ones to assess the transition in progressive form and extend it to the whole system [7,66]. Similarly, all the factors and actors are accommodated comprehensively to transition from tradition to a regenerative supply chain [67,68]. The theory helps in developing and enhancing resilience mechanisms to face the challenges, accordingly, propose strategies and action plans, and offer new insights to bolster Resilience in supply chain management processes and practices [1,33]

4.4. Theoretical framework of the study

The above-cited theories provide a comprehensive framework for assessing and developing Resilience in the supply chain management processes and practices, especially in the context of RSCM. RT focuses on and aligns environmental Resilience with RSCM. It recommends having a robust mechanism to understand how the supply chain can adopt, adapt, recover, and maintain functionality in disruptions [41,57]. It also integrates flexibility, redundancy, and learning plans to boost Resilience in supply chain processes and practices, which is the core of RSCM [62]. Moreover, RT aims to enhance the adaptive capacity of the supply chain, facilitate rapid response to unforeseen situations, and foster regenerative processes and practices to contribute to environment restoration and enhancement [62] actively.

While CAST and TMT offer valuable insights into the dynamic nature of supply chains and managing transitions, they may not address the intricacies of environmental Resilience and regenerative practices as comprehensively as RT [40,44]. However, integrating elements of CAS, such as emergent behaviours and self-organization, and strategies from TMT, such as multi-stakeholder involvement and governance mechanisms, alongside RT could provide a holistic approach to navigating the transition to RSCM while enhancing environmental Resilience within supply chains [49,61].

In Table 3 and Figure. 1 summarize the above-cited theories and compare them logically and coherently.

Table 3. Synthesis of the theories.

Theory	Identify Key Concepts	Comparison and Evaluation
RT	Resilience, adaptability, recovery, disturbance absorption, system functionality	It focuses on the system's ability to bounce back after disturbances, adapt to changes, absorb shocks, and maintain functionality.
CAST	Decentralization, adaptability, emergent behaviours, self-organization, feedback loops	It focuses on decentralization, adaptability, emergent behaviours, self-organization, and feedback loops.
TMT	Transition, change management, governance mechanisms, multi-stakeholder involvement	It focuses on transition, change management, governance mechanisms, and multi-stakeholder involvement.

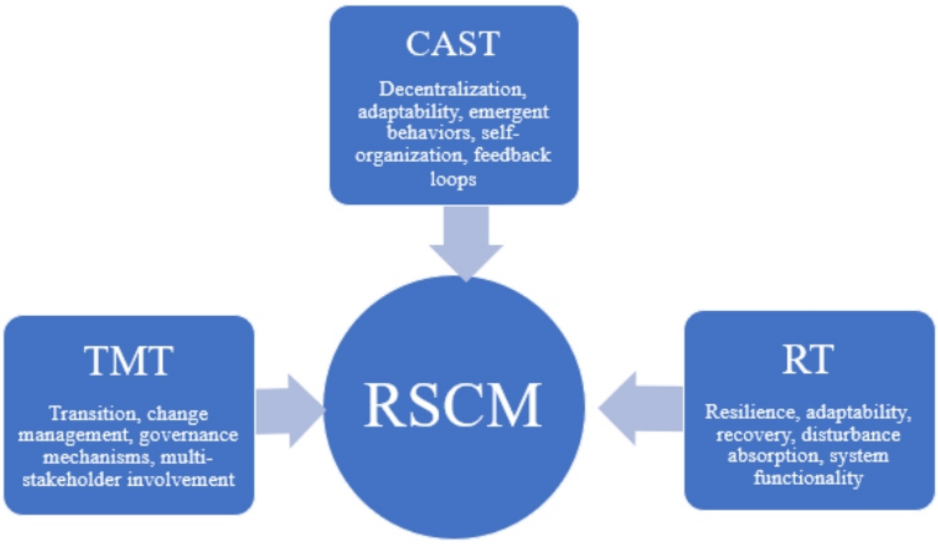

Figure 1. Theoretical framework for the study

5. Methodology

The study adopted a qualitative approach. For this, in the first phase, a comprehensive review was conducted to explore the regenerative supply chain management concept, and its comparison was made with green supply chain management. In the second phase, a structured qualitative interview was conducted to explore the phenomenon of interest in more detail. Qualitative structured interviews were found suitable to get the explicit and empirical experiences of concepts and constructs [4,69]. Interviews are a better measure to collect in-depth insights regarding phenomena of interest. The questions for the interview were developed and discussed with the academicians and language experts for face and content validity. Each interview took almost 40 to 45 minutes. The interview wasrecorded,and transcription was also taken, which was shared with the respondents for confirmation. After aggregative response development, the theme was also shared with the respondents for confirmation in the second round. The authors themselves conducted all the interviews in person. The interview started with formal questions (attached in Appendix A) supported by other formal queries, depending on the respondents' responses. The main open-ended questions were "How can organizations enhance environmental Resilience during the transition to regenerative supply chain management? This question was divided into sub-questions to formally get the answer and building blocks for the thematic analysis.

5.1. Sample/sampling

The area is new for the researchers and the practitioners. Therefore, the total population was unknown. Thus, the study adopted snowball sampling to approach only those with the related skills, qualifications, and experiences regarding green and regenerative supply chain management. Thus, all the respondents were approached based on this specialized cohort's recommendations, identification, and referral basis. Thus, 17 respondents were approached by different business professionals, university professors (supply chain management), and national and international organizations working on regenerative supply chain practices in the NEOM (A multi-billion project in Saudi Arabia). However, some of the participants did not agree to respond, and some of the respondents gave half the answers (incomplete interview). The study included the responses of eleven (12) respondents, and their details are given in the demographic Table 4.

Table 4. Demographics of the study.

Items		Frequency	Percentage
Type of organization	University	3	25%
	Business Professional	4	33%
	NGO/INGO	5	42%
Gender	Male	7	58%
	Female	5	42%
Marital Status	Married	7	58%
	Un-married	5	42%
Professional experiences	1–10 years	6	50%
	11–20 years	3	25%
	30–40 years	3	25%
Age	30–35	4	33%
	36–40	7	58%
	41–50	1	9%
Job	Full time	12	100%
	Part-time	0	0%

5.2. Ethical considerations

The study strictly adhered to ethical considerations throughout the study, ensuring participant confidentiality and anonymity in data collection and analysis. Informed consent was obtained from all participants, and ethical guidelines regarding research conduct were rigorously followed, prioritizing the well-being and rights of the individuals involved. The interviews were conducted at the respondent's defined time (allocated time). The study was also faired to give representation to both male and female respondents.

5.3. Data collection

The author approached the interviewee personally. They were contacted and approached, got their consensus for the interview, and then were formally asked/questioned for the framed (attached in Appendix-A) questions. Respondents were asked for help, clarification, explanation, and elaboration. They were also given the freedom to stop the interview at any time. Similarly, codes were developed for the participants instead of using their data.

5.4. Data analysis

In our data analysis phase, the study employed a first narrative analysis and, in the second stage,a thematic analysis approach to distill and interpret the qualitative information gathered from structured interviews with respondents. This method systematically examined the interview transcripts and notes to identify recurring patterns, topics, and significant ideas. Additionally, the study carefully reviewed the collected data, noting common threads, concepts, and key points shared by the participants. Instead of a formal coding process, we focused on organically identifying prevalent themes and patterns in the interviewers' narratives. These emergent themes were then grouped and organized based on their similarities, allowing us to generate a conceptual framework. Moreover, NVIVO-11 was used to generate the word cloud from the interview responses.

6. Findings of the interviews

6.1. Narrative analysis

The first question of the interview was regarding the definition of Resilience in supply chain management. For this question, they (PB1, PIO1, and the SCF1) that *"Resilience within supply chain management refers to the system's capacity to anticipate, adapt, and recover swiftly from disruptions while ensuring continuity in operations. It involves proactive risk management, adaptability, flexibility, and maintaining essential functions during disturbances. They proclaimed that "recycling, reusing resources, or developing closed-loop systems can bolster resilience."* Similarly, they added to the response of the contribution of RSCM to long-term sustainability goals, *"RSCM contributes positivelyto long-term sustainability goals. It promotes circularity, reduces waste, and conserves resources. At the same time, it fosters Resilience in the supply chain. Moreover, It aligns business operations with environmental and social considerations. Also, it aims for sustainable growth through minimizing negative environmental impacts."*

The second question asked by the respondents was about the potential impact of RSCM on enhancing supply chain resilience. The aggregative response from PB1, PIO1, and SCF1 was "

"RSCM presents enhances Resilience in supply chains. Through circularity, waste reduction, and ecosystem conservation, the supply chain becomes more accommodated, flexible, and interconnected. It mitigates risks associated with climate, resource scarcity, and market fluctuations. These also reduce vulnerabilities and ensure continuity of operation in crises and disruptions. Moreover, it aligns

sustainability goals with operations that develop and foster Resilience and innovation."

Similarly, they (PB2, PIO2, and the SCF2) responded to changes or adaptations necessary for RSCM implementation: *"RSCM implementation requires extensive orientation and restructuring inside the organizations. Collaboration with stakeholders and adaptation of innovative technologies are needed for traceability and transparency. Similarly, revamping procurement strategies and establishing clear guidelines for regenerative supply are needed from ethical and organizational perspectives. Additionally, cross-sector collaboration, a culture of knowledge sharing, and support are essential in implementing RSCM."*

In the same way, they (PB3, PIO3, and the SCF3) anticipated barriers and plans to address transitioning from GSCM to RSCM."

"There can be certain challenges to transit from GSCM to RSCM initially. These may include, but are not limited to employees' training and awareness, upgrading technology, onboarding stakeholders, and overcoming communication problems. However, these will bring long-term benefits like stakeholder engagement, industry-wide collaboration, establishing benchmarks and frameworks, which will facilitate the smoother transition and overcome transition."

For the RQ3 regarding the role of stakeholders in RSCM implementation, they responded that.

"Active participation of the stakeholder is crucial for successful RSCM implementation. Their involvement, commitment, and contribution are essential for RSCM practices and processes. It fosters collaboration across industries in the supply chain" in the same way they added to the collaboration with suppliers and stakeholders for the RSCM transition."

Collaboration comes through active partnership based on a shared vision, shared values, knowledge exchange, and joint development of strategies. These practices help facilitate the smoother transition to RSCM and its implementation." Additionally, the respondents answered regarding the strategies for stakeholder alignment during RSCM transition, they proclaimed that *"ensuring alignment involves fostering inclusivity, transparent communication, and stakeholder engagement. Implementing feedback mechanisms, capacity-building programs, and establishing clear roles and responsibilities are crucial for maintaining stakeholder cooperation and alignment throughout the transition."*

In the end, for the last question, RQ4, regarding the measurement of RSCM success within the supply chain, they responded that the *"industry needs to develop success measurement for tracking progress like waste reduction, increased resource efficiency, supplier collaboration, cost savings, and customer satisfaction to gauge the effectiveness of RSCM implementation."* In the same way, for the answer regarding the key performance indicators (KPIs) for RSCM impact evaluation, they proclaimed that " *the Prioritized KPIs aims to evaluate the diverse dimensions of sustainability and Resilience, needed for the RSCM implementation. It includes, but not limited to carbon footprint reduction, waste management, supplier sustainability, resilience indices, and social impact assessments, aiming to evaluate the diverse dimensions of sustainability and Resilience influenced by RSCM." Similarly, to respond to the query regarding challenges in quantifying benefits of RSCM implementation, they declared that "there are many challenges regarding the standardizing measurement methodologies, accessing reliable data across the supply chain, attributing causality between RSCM practices and observed impacts, and harmonizing diverse metrics. Addressing these challenges would require collaborative efforts, industry-wide standards, and innovative measurement tools to effectively quantify RSCM benefits."*

These responses collectively urge the integral role of Resilience in supply chain operations. It emphasizes proactive measures of adaptability and sustainable practices of RSCM. They proclaim the potential of RSCM in sustaining the supply chain against disruption. The responses also suggest restructuring of the organization, active stakeholder engagement, and technological innovation for the successful implementation of RSCM. Moreover, the experts postulated that in the transition from GSCM to RSCM, there may be some temporary challenges; however, it will bring long-term benefits to the industries.

Similarly, stakeholder recognition and active engagement help identify KPIs for measuring RSCM across the supply chain ecosystem. The study came up with the following major themes extracted from the interview responses, presented in Table 5 and Figure 2. These responses presentthree major perspectives regarding RSCM.

Table 5. Themes extracted from interviews.

Themes	Professional Businessman	Professional (Sustainable International Organization)	Professor of Supply Chain Management
The Potential impact of RSCM on Supply chain resilience	-Bolster supply chain resilience through regenerative practices -Reduce risks related to disruptions -Emphasize circularity and waste reduction	-Fortify supply chain resilience -Mitigate disruptions due to climate change and resource depletion -Focus on holistic sustainability	- Transform supply chain resilience through regenerative practices -Create adaptable systems –Promote proactive risk mitigation
Changes/Adaptations for RSCM implementation	-Shift towards collaborative relationships -Invest in technology for traceability - Establish new metrics - Foster a culture of innovation and sustainability	-Holistic reorientation towards sustainable practices - Revamp procurement strategies -Foster collaboration and knowledge sharing	-Comprehensive restructuring of supply chain strategies integration
Barriers/Concerns in transitioning to RSCM	-Initial investment for technology upgrades -Resistance/skepticism among stakeholders -Address through communication and training programs	-Shift in mindset and supply chain structures -Address through stakeholder education and collaboration with industry leaders	-Resistance due to operational norms and uncertainties -Address via detailed roadmaps and collaboration with experts
Role of stakeholders in RSCM implementation	-Offer support, expertise, and resources -Ensure adoption of regenerative practices throughout the supply chain	-Act as active participants and influencers -Embrace regenerative practices and sustainability principles	-Drive RSCM implementation -Embed regenerative practices and foster collaboration
Collaboration with stakeholders for RSCM transition	-Open communication and shared goals -Joint projects and co-development of strategies -Engagement with stakeholders	-Partnerships based on shared values and knowledge sharing -Supplier development and sustainability-focused forums	-Strategic partnerships and co-development of roadmaps -Joint research initiatives and idea-sharing
Strategies for stakeholder alignment during transition	-Clear communication channels and stakeholder mapping -Encouragement of participation in decision-making -Offer incentives and resources	-Foster inclusivity and transparent communication -Feedback mechanisms and capacity-building programs	-Establish shared goals and engagement sessions -Continuous communication and empowerment through training and incentives
Measurement of RSCM effectiveness in the supply chain	-Track metrics like waste reduction and resource efficiency -Assess cost savings and improved relationships	-Monitor waste reduction and supplier compliance -Measure improvements in well-being and ecosystem health	-Evaluate waste reduction, supplier collaboration, and agility - Assess cost savings and customer satisfaction levels
Specific KPIs for evaluating RSCM impact	-Carbon footprint reduction and recycled materials usage -Energy efficiency and supplier compliance -Swift recovery from disruptions	-Biodiversity preservation and emissions reduction -Water conservation and supplier diversity -Swift recovery from disruptions	-Carbon footprint reduction and circularity index -Supplier sustainability ratings and resilience index -Social impact assessments
Challenges in quantifying RSCM benefits	-Difficulty in measuring intangible impacts -Establishing benchmarks and consistent data collection	-Standardizing measurement methodologies and accessing reliable data -Attributing causality between practices and impacts	- Data availability and cause-and-effect relationships -Harmonizing diverse metrics across the supply chain

Figure 2. Word cloud from the interview responses.

The study also developed a conceptual framework that highlighted the transition from GSCM to RSCM. This model encapsulates major elements, contributing factors, and challenges faced during the transition. It is presented in Figure 3.

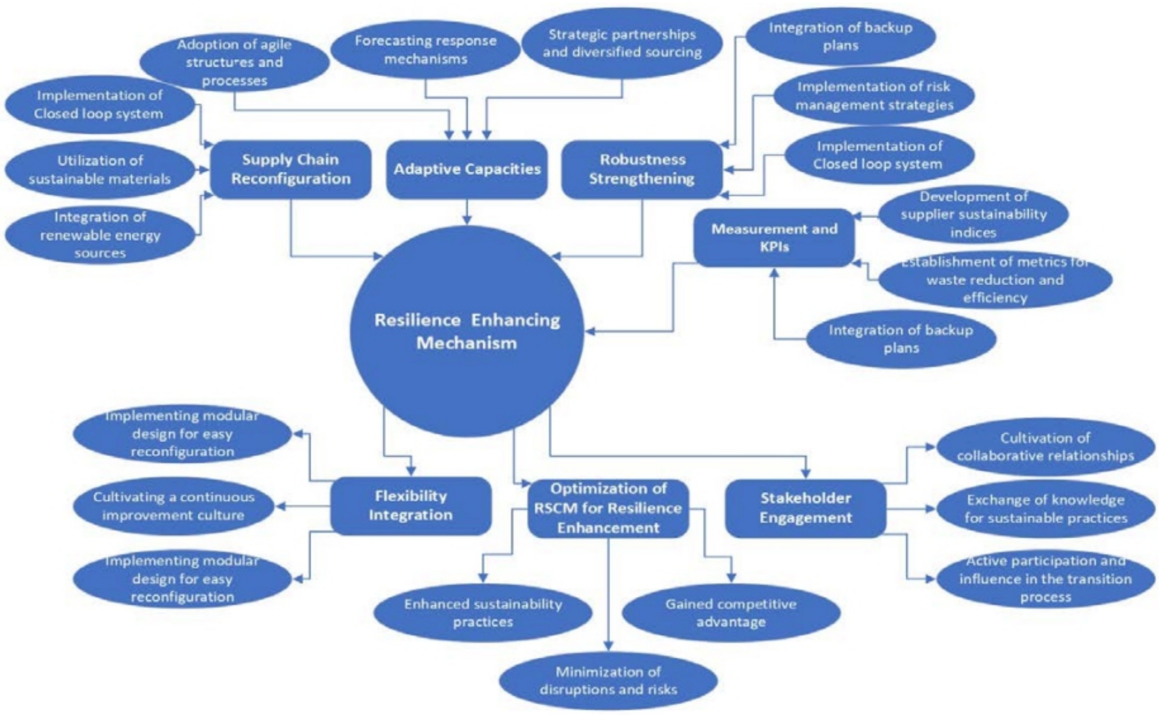

Figure 3. Resilience enhancing mechanism.

In the context of RSCM, the focus shifts towards building Resilience and fostering regenerative practices that contribute to sustainability and positive impacts on the environment and society [14]. Within the RSCM framework, logical planning involves anticipating and mitigating disruptions andaligning strategies with regenerative principles. Contextual considerations extend beyond immediate operational factors to encompass broader ecological and social contexts, ensuring supply chain activities contribute to regeneration rather than depletion [12]. Sectoral insights within RSCM involve tailoring mechanisms to industry-specific risks and opportunities for regenerative practices. A research-based approach includes studying regenerative techniques, circular economy principles, and sustainable innovations [59]. Connectivity is vital for sharing regenerative best practices, collaborating on eco-friendly initiatives, and collectively working towards a regenerative supply chain. So, resilience-enhancing mechanisms within the RSCM framework should fortify against disruptions and actively contribute to the regeneration and sustainability of the supply chain and the ecosystems in which it operates [31,47,66].

7. Discussion

The evolution from GSCM to RSCM marks a significant paradigm shift in sustainability practices within the broader context of supply chain management [63]. Prior discussions and comparative analyses from various studies have underscored this transition as a pivotal move from merely minimizing negative impacts to actively restoring and enhancing ecosystems while conducting business operations [33]. This transformation reflects a departure from the linear and reductionist approach of GSCM towards a holistic and regenerative model rooted in concepts like circular economy, biomimicry, and cradle-to-cradle design [8,54,61]. The debate gathered from previous studies highlights that while GSCM primarily focuses on reducing harm through eco-efficiency, RSCM aims to mimic nature's processes and emphasizes closed-loop systems, renewable energy sources, waste reduction, and sustainable materials. This discussion explored a clear difference between the two approaches and the need for transition to RSCM [53].

Similarly, the comparative analysis found that the GSCM concentrates more on reducing negative impacts by optimizing resource usage and efficiency in the supply chain [31]. However, RSCMrecommends minimizing the negative impact and actively focusing on the restoration and improvement of the ecosystem. Moreover, RSCM also aligns its processes and practices with the fundamental principles of circular economy, Resilience, closed-loop systems, renewable energyutilization, and sustainable material practices [16,54]. This comparison admits the need for a more holistic, nature-mimicking approach. Also, it highlighted the need for GSCM in achieving the broader sustainability goals that RSCM is striving for [43].

Moreover, the study also explored commonalities. Both approaches (GSCM and RSCM) observethe critical role of resilience resilience and strive for sustainability [43,65]. However, RSCM seeks more emphasis on developing capacities and raising awareness regarding sustainability, robustness,flexibility, and agility. Moreover, the resilience-enhancing mechanism is the hallmark of RSCM, which demands comprehensive exploration and integration of resilience-building strategies in the supply chain domain. [2,53].

7.1. Theoretical Implications

The study added to the body of knowledge in supply chain management. The merging of the three theories (RT, TMT, and CAST) came with a robust theoretical framework to understand the dynamics of the RSCM. The synthesis of theory provides an understanding of how supply chain management practices and processes proactively contribute to regenerative practices. The framework explored and developed the resilience-building mechanism within RSCM. The adaptive capacity, robustness, and flexibility add to the existing theories. These theories can be aligned practically when shifting from GSCM to RSCM. Moreover, the study bridges the gaps in understanding the specific role of the resilience-enhancing mechanisms in the transformative processes. Additionally, the theoretical framework proposed can serve as a foundational guide for future research endeavours exploring the intersection of sustainability, Resilience, and supply chain management

7.2. Practical Implications

Besides theoretical contribution, the study also offers actionable insights to the businesses. It advises adopting RSCM practices to reduce waste, enhance robustness, and promote flexibility and agility in their operations and practices. These practices also add to the social impact of the business, where the public starts accepting and adopting. Moreover, these practices bring a tangible matrix for measuring RSCM success.

Moreover, the study also recommends the inclusion of the stakeholders and recognizes their critical role in promoting Resilience and adapting to RSCM processes and practices. Including active stakeholders brings collaborative relationships, improves transparency, and promotes effective communication and stakeholder engagement. Moreover, the study proclaims that these practices must be exercised beyond internal organizational to broader industry collaborations, emphasizing the importance of cross-sector partnerships and knowledge sharing. Lastly, the study came up with the indicator or key performance indicators, which can be set and promoted to be adopted across industries.

8. Limitations of the study

The study on RSCM and its transition from GSCM has made significant contributions, shedding light on the transformative paradigm shift in sustainability practices within supply chains. However, limitations need to be considered for future research. A more robust approach would involve cross industry analysis to explore the challenges and opportunities in diverse business contexts. Additionally, while the qualitative insights from expert interviews provide valuable perspectives, future research could benefit from a mixed-methods approach, incorporating quantitative data to bolster the statistical validity of findings. Furthermore, the study's reliance on data up to a specific date may miss recent developments in the dynamic field of sustainability, urging researchers to update their investigations continually. Moreover, the proposed theoretical model can be tested and validated using qualitative or quantitative methods in different domains.

9. Conclusion

The study explored and assessed the evolution from GSCM to the transformative paradigm of RSCM. The interviews' findings admit the critical role of RSCM in bringing and bolstering Resilience in the supply chain. The study debated the fundamental philosophy of RSCM. It explored circular economy principles and biomimicry, which actively contribute to restoring ecosystems while conducting business operations. The study also emphasizes closed-loop systems, renewable energy utilization, waste reduction, and sustainable material adoption.

The study also carries certain limitations, which need to be considered in future studies. The constrained sample size and the qualitative approach, broader industry representation, and diversemethodology can be explored in the future to comprehend better the concept, processes, and implications of RSCM. In the same way, the integration of RSCM principles is a desirable shift towards sustainability and supply chain resilience. In line with the study's findings, future research may focus on diverse sectors, domains, and methodologies. It can also incorporate alternative theoretical models and methods for the multifaceted implementation of RSCM. Furthermore, longitudinal and cohort studies will be beneficial in exploring the behavioural aspects and preferences of the general population regarding RSCM.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The author declares no conflict of interest.

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Using DEMATEL, clustering, and fuzzy logic for supply chain evaluation of electric vehicles: A SCOR model

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A B S T R A C T

The transportation sector is considered among the major sources of greenhouse gas emissions. Given advancements in transportation technology, customers' willingness to reduce carbon footprints, as well as policy incentives, Electric Vehicles (EVs) are becoming an increasingly important part of the passenger vehicle industry. Evaluation of Supply Chain (SC) performance in the EV industry seems to contribute significantly to the enhancement of the operational consequences across the supply chain tiers. The SCOR (Supply Chain Operations Reference) model was designed to help businesses optimize their supply chain operations, reduce costs, and improve customer satisfaction. Although many performance measurement models have been developed in the context of SC, there is no performance measurement model in relation to the EV supply chain based on indicators of customer perceived value (Reliability, Responsiveness and Agility) in the SCOR model. Therefore, we aimed to develop a new method to evaluate the performance of the EV supply chain using a set of critical SC performance evaluation indicators. Multi-criteria decision-making along with machine learning was used in order to develop a new method for evaluating SC performance. We used k-means clustering and fuzzy logic approaches in the development of the new method. An assessment of indicators' importance level was performed using the fuzzy logic approach. The results of the method evaluation show that the proposed method is capable of predicting the performance of the EV supply chain accurately. According to the results, by optimizing their supply chain, companies can improve their ability to deliver products and services that meet or exceed customer expectations, resulting in higher customer perceived value and customer satisfaction.

Keywords: fuzzy logic; DEMATEL; electric vehicles; supply chain performance; SCOR metrics

1. Introduction

Transportation is one of the major sources of greenhouse gas emissions [1]. Sustainable transportation is essential for reducing greenhouse gas emissions, mitigating climate change, and promoting a healthier and cleaner environment. Sustainable transportation recently gained the attention of many researchers [2,3]. Currently, significant 2 learning are used in order to develop a new method for evauating SC performance. We used k-means clustering and fuzzy logic approaches in the development of the new method. An assessment of the indicators' importance level is performed using fuzzy logic through fuzzy inference system. This method can help to achieve accurate prediction of supply chain performance in uncertain conditions with learning abilities as well as better interpretable results.

1.1. Research problems and contributions

Although many performance measurement models have been developed in the context of SC, there is no performance measurement model in relation to the EV supply chain based on indicators of customer perceived value (Reliability, Responsiveness, and Agility) in the SCOR model. Customer perceived value is an essential concept in transportation, as it represents the customer's perception of the benefits and costs associated with a transportation service. In transportation, CPV plays a critical role in determining customer satisfaction and loyalty. For example, if a customer perceives that a transportation service provides high customer perceived value, they are more likely to use that service again and recommend it to others. Furthermore, transportation providers should continuously monitor and analyze customer feedback to identify areas for improvement and adjust their services accordingly. This can help to maintain high levels of customer perceived value, which is critical for long-term success in the transportation industry. High customer perceived value can also lead to improved collaboration and communication within the supply chain. When customers perceive that the supply chain provides high-quality products or services, they are more likely to engage with the supply chain and provide feedback, which can help the supply chain to identify areas for improvement and optimize its operations accordingly.

We develop an expert system for supply chain performance evaluation using multi-criteria and machine learning approaches. Computational tools assist organizations to discover suitable knowledge required by assessment systems for SC performance to address serious managerial challenges and supply them with proper decision support platforms. These systems have become more popular in recent years because of their potential to apply human expert knowledge as rules to solve complicated problems in a determined field. Besides this important role in the research on the measurement of SC performance, the present work has also provided useful guidelines to develop, train, and validate computational models according to machine learning strategies. Thus, it has a significant role in the enhancement of measurement tools that assist managers in decision-making in the area of SC management.

Multiple-Criteria Decision-Making (MCDM) techniques have been effective in the development of models and systems based on several criteria. MCDM methods provide a comprehensive framework for evaluating and optimizing transportation systems and enable transportation planners and policymakers to prioritize and allocate resources efficiently. MCDM techniques such as the Analytic Hierarchy Process (AHP) [4], Analytic Network Process (ANP) [5,6], Decision Making Trial and Evaluation Laboratory (DEMATEL) [7,8], Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [9,10] and fuzzy MCDM [11] are widely used in the transportation context. This paper develops a new hybrid method to identify the weights of SCOR model criteria for SC performance evaluation. The method uses the DEMATEL which is widely used in decision-making problems [8,12]. We use fuzzy logic approach for SC performance evaluation. Since performance measurement is a complicated process, it is inevitable to use qualitative linguistic terms. Moreover, subjectivity and uncertainty are the typical features of the respondents' perceptions regarding the likelihood and effects of performance indicators. It is possible to address the problem of subjective judgments through fuzzy logic. Expressing fuzzy variables in a mathematical logic becomes possible using fuzzy evaluation. Such systems can address quantitative and qualitative information in an effective way. They are promising for SC performance applications since the incorporation of qualitative expert heuristic knowledge in the process of constructing the model is facilitated through them. Fine-tuning of the model is possible using quantitative historical/experimental data. Accordingly, more robustness and accuracy of the model is obtained along with easier interpretability. Interpretability of the model is critical in the assessment of SC performance.

The proposed system is based on the SCOR model which combines the performance metrics with modeling and simulation strategies to support management actions, including assessment of SC performance, assessment of risk, evaluation of suppliers, and benchmarking. Nevertheless, applications based on SCOR introduced in previous studies mostly concentrated on the measurement of SC performance through multi-criteria decision-making approaches. We, however, take advantage of the SCOR model for the SC performance evaluation in the EV supply chain using machine learning and multi-criteria decision-making approaches.

Finally, we use decision trees to implement fuzzy logic approach. The decision trees technique is widely used in prediction tasks in transportation studies [13,14]. We use Classification and Regression Tree (CART) approach to automatically discover the decision rules from the data for SC performance evaluation. These rules are used in the fuzzy logic approach to identify the associations of the input and output variables, with no requirement to make parameters of variables as well as decision rules manually. This can be a positive point of the suggested method compared to those that are merely dependent on fuzzy inference as the problems in providing a definition for appropriate linguistic terms and relative fuzzy numbers can be an important weakness of these systems. Besides, the exponential growth of the decision rules is possible according to the number of indicators and linguistic terms which make the rule base system design more complicated. Therefore, adjustment of the inference system seems to be a learning process, involving a team of experts in the area of SC performance and fuzzy inference in the real application.

2. Supply chain management and evaluation

The supply chain has brought competitive advantages [15–17] toward achieving time to market with the highest efficiency and effectiveness while considering meeting the customers' expectations [18–20]. Therefore, supply change management has changed into a critical component of successful firms. According to [21], supply chain management is systematic which includes the complicated issue of management of all the processes associated with the supply chain in a range of raw materials sourcing to the provision of post-purchase customer services.

All companies that seek to grow and gain profits at the global level need to consider supply chain management as a vital issue [22–24]. The supply chain is regarded as a series of integrated business processes which consist of all actions related to the goods flow and change, including different stages of raw materials to the transfer of finished products to the final consumers [25]. The establishment of the tactical association with suppliers as well as consumers, long-term relations, information sharing, and working together to promote products and processes are included in the supply chain management [26]. Consequently, different benefits, including reducing the inventory, improving resource usage, and higher customer satisfaction are only a few examples [27]. Thus, measurement of SC performance focused on the assessment of how effective supply chain management techniques and methods work seems of extreme importance. Evaluation problems of supply chain performance are associated with a broad scope of measuring independent organizations' performance within supply chains for the measurement of the performance of the overall supply chain system. These problems are among the most extensive strategic decision problems which should be taken into account in long term effective operations of the total supply chain. Conventionally, independent operation of marketing, distribution, planning, manufacturing and purchasing organizations has been common. Previous research in the area of SC performance measurement consists of a broad scope of studies such as conceptual frameworks of metrics [28], research on the identification of most frequently applied metrics [29], case studies [30] as well as quantitative research models to support performance measurement processes [31].

3. SCOR model

The Model of SCOR developed by the Supply Chain Council (SCC) is an effective approach for supply chain management [32,33]. The Supply Chain Council as a non-profit institution developed this reference model for implementation of a standard to model thorough internal as well as external supply chains. A four-level hierarchical pyramid structure is designed for the SCOR model, indicating a plan to improve the performance of the supply chain. Three levels of the processes are addressed by the model and each level continuously increases in terms of process details as well as specificity [34]. Functional and organizational tasks than processes are addressed at level 4, in which supply chain changes are implemented according to the design generated by the SCOR model. Level 1 which is at the top, helps to define the SCOR model's range and contents, while five management processes are determined, including planning, sourcing, making, delivery, and return. The domain and parameters of the overall sub-processes in the supply chain are set by these main management processes. Moreover, five performance characteristics of the supply chain are identified at level 1 by the SCOR model. The first three features, including reliability, responsiveness, and flexibility, are adjusted toward the customer. Attributes of cost and assets are considered with internal focus. Ten metrics of level 1, which can be used by the organizations in the measurement of organizational goal achievement and success, are associated with these features. It is worth noting that organizations are not likely to obtain the best practices in all of the desired metrics. Thus, metrics selected by the organizations as the focus, need to represent the customers' demands.

The process element level is included in Level 3 which practices in-depth exploration of the organizational detailed works along with information flow across the organizational supply chain. Accordingly, chief transactions of input and output look at goals, metrics of performance, the best methods, and the infrastructures of the systems, as well as their supporting potentials, are at the center of focus. Validation of the effects of promotions across the supply chain can be performed at this level. Levels 2 and 3 are aligned to relative performance standards as well as organizational systems and interactions. Implementation of supply management methods is performed at the next level whose activities is unique for each organization and is concentrated on the implementation of tasks. The activities of level 4 consist of concentration on organizational design, processes, systems, as well as individuals across the organization. However, given that every organization has its implementation process, these activities have not been incorporated in the SCOR model. According to the SCOR® model, a series of performance standards are proposed in three hierarchical layers. Figure 1 indicates the SCOR model's organizational structure. Performance attributes of Level 1 and Level 2 indicators are presented in Table 1.

4. Method

A new method is developed in the present work to evaluate the performance of the EV supply chain using a set of significant measurement indicators in the SCOR model (see Figure 2). Development of the method was carried out by application of multi-criteria decision making as well as machine learning techniques. In the first step of the method, we employed a multi-criteria decision making approach, DEMATEL, to reveal the importance level of measurement indicators. Then, fuzzy logic was utilized to assess the significance level of indicators for measuring SC performance. To do so, we applied the decision trees method to discover the decision rules to be used in the fuzzy logic approach. The present research concentrates on customer-focused indicators that have been supplied in the SCOR model. The indicators are presented in Table 2 [35]. An introduction to the methods is presented in the following sections.

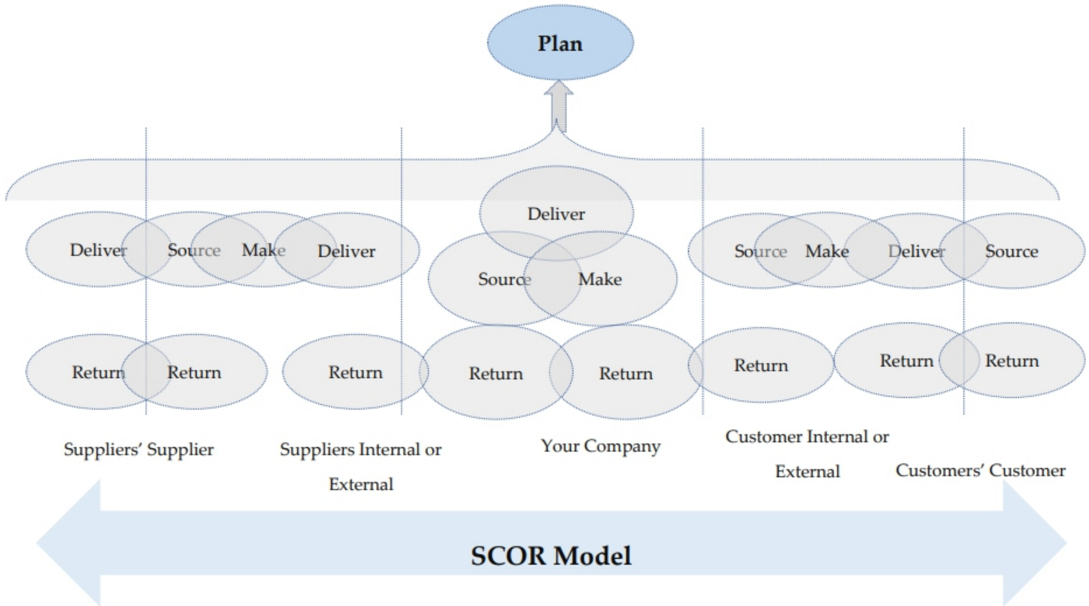


Figure 1. The organizational structure of the SCOR model.

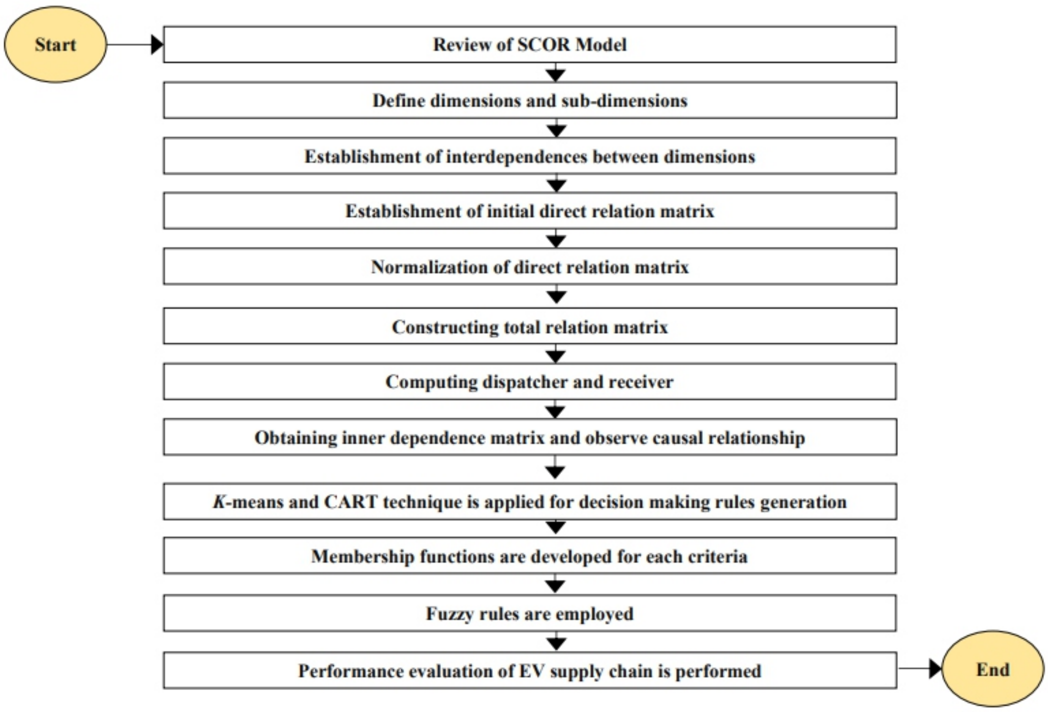


Figure 2. The proposed method.

Table 1. Performance attributes and level 1 and level 2 indicators.

Focused group	Attribute	Level 1 Indicators	Level 2 Indicators
Internal	Cost	Total cost to serve	Planning Cost
			Sourcing Cost
			Material Landed Cost
			Production Cost
			Order Management Cost
			Fulfillment Cost
			Returns Cost
			Cost of Goods Sold
	Assets	Cash-to-Cash Cycle Time	Days Sales Outstanding
			Inventory Days of Supply
			Days Payable Outstanding
		Return on Supply Chain Fixed Assets	Supply chain fixed assets
		Return on Working Capital	Accounts Receivable (Sales Outstanding)
			Accounts Payable (Payables Outstanding)
			Inventory
Customer	Reliability	Perfect Order Fulfillment	Delivery Performance to Customer Commit Date
			Documentation Accuracy
			Percentage of Orders Delivered In Full
			Perfect Condition
	Responsiveness	Order Fulfillment Cycle Time	Source Cycle Time
			Make Cycle Time
			Deliver Cycle Time
	Agility	Upside Supply Chain Flexibility	Source: Upside Flexibility
			Make: Upside Flexibility
			Deliver: Upside Flexibility
			Source: Upside Return Flexibility
			Deliver: Upside Return Flexibility
			Source: Upside Return Flexibility
			Deliver: Upside Return Flexibility
		Supply Chain Upside Adaptability	Source: Upside Adaptability
			Deliver: Upside Adaptability
			Make: Upside Adaptability
			Deliver: Upside Return Adaptability
			Source: Upside Return Adaptability
		Supply Chain Downside Adaptability	Make: Downside Adaptability
			Deliver: Downside Adaptability
			Source: Downside Adaptability
		Overall value at risk	Risk rating
			Source: Value at Risk
			Deliver: Value at Risk
			Plan: Value at Risk
			Make: Value at Risk

4.1. Fuzzy logic approach

The fuzzy set theory was suggested in [36] to represent knowledge according to the degrees of membership instead of the crisp membership, which is defined in classical binary logic [37]. The Membership Function (MF) is the major concept in fuzzy logic, which is the numeric representation of the degree according to which an element is assigned to a set. An MF describes the fuzzy set through the assignment of a degree of membership to every element, which can be realized through mapping every point of the input space, named the universe of discourse, to a membership value between 0 and 1. Various kinds of membership functions can be considered [38–42]. Nevertheless, Triangular, Trapezoidal, and Gaussian can be mentioned as the most common cases. Typically, more than one MF is employed for every input variable since a single MF can just describe one fuzzy set. The first stage of the fuzzy logic control process includes identification or looking for the input/output membership functions. Categorization of the information that enters a system is performed by the fuzzy algorithm, after which values indicated the degree of membership in every category is assigned. In rule-based applications of fuzzy logic, membership functions seem to be related to terms observed in the antecedents or results of rules (see Figure 3).

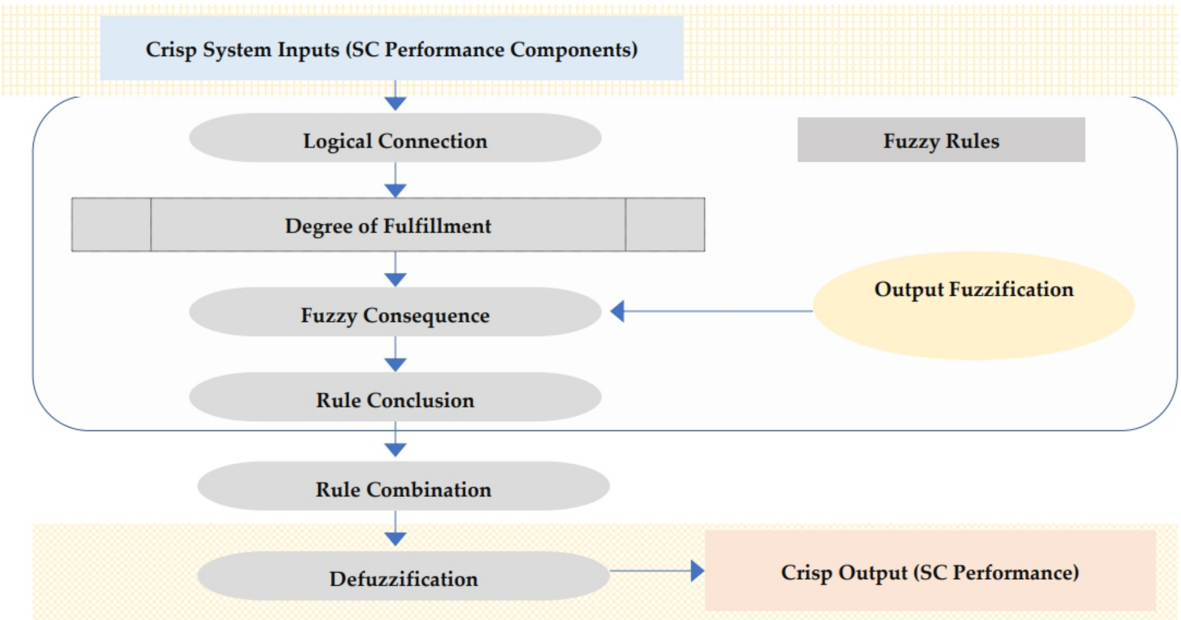


Figure 3. Fuzzy logic modeling procedure.

Table 2. Customer-focused indicators.

Attribute	Description	Level 1 Indicators	Description
Reliability (C1)	Reliability is defined as the capacity to fulfill tasks as anticipated, with a primary emphasis on the predictability of process outcomes.	Perfect Order Fulfillment (C1.1)	The percentage of orders for which delivery performance is met, as measured by the presence of delivery damage and the availability of complete and accurate documentation.

Responsiveness (C2)	Responsiveness pertains to the swiftness with which tasks are executed, specifically, the pace at which a supply chain delivers products to the consumer.	Order Fulfillment Cycle Time (C2.1)	The typical actual cycle time that is consistently achieved to fulfil orders placed by customers.
Agility (C3)	Agility refers to the capacity to react to external influences, specifically, the capability to adapt to market changes with the aim of gaining or retaining a competitive edge.	Upside Supply Chain Flexibility (C3.1)	The number of days needed to achieve a 20 percent increase in delivered quantities that was not planned.
		Supply Chain Upside Adaptability (C3.2)	The highest possible percentage increase in quantity delivered that can be accomplished in a period of 30 days that is still considered sustainable.
		Supply Chain Downside Adaptability (C3.3)	The decrease in ordered quantities can be maintained up to 30 days before the delivery date without resulting in any inventory surplus or additional costs.
		Overall value at risk (C3.4)	The sum of the probabilities of risk events occurring in key supply chain functions, when multiplied by the financial impact of these events.

4.2. Decision trees

Classification and Regression Tree (CART) is a computational–statistical algorithm for generating predictions in the form of a decision tree [43]. The CART technique is a method used to partition data into final nodes (child nodes) using a series of binary splits which begin at a parent node [44–48]. By binary split, it is meant that every node can split into just two fresh nodes at a split level. The partition is repeated by CART for every child node, going on in a recursive manner until the uniform level in the desired general node can be acquired or a specific ceasing criterion is considered. Normally, the modeling algorithm stops if the maximum tree depth determined by the user is achieved or in the case that it is not possible to make more splits since no considerable predictor variable has remained to split the node. The CART splitting algorithm in every node works according to the notion that every child node needs to have higher "purity" compared to the original parent. "Purity" represents a notion associated with the values of the desired variable leading to zero variance between the splitting stages. The splitting procedure forms a tree structure according to a set of "if–then" rules which provide the decision-makers with the required guidance. The tree structure output of CART supplies information on the major factors and interplay of critical components for SC evaluation in a conveniently interpretable manner.

4.3. DEMATEL

DEMATEL was suggested for the first time by the Battelle Memorial Institute via its Geneva Research Centre [49]. This technique is widely used in solving decision-making problems where the interdependencies among the criteria are considered vital in their evaluation [50–52]. The DEMATEL methodology is defined in the following brief stages [53]:

Stage 1: Calculation of the primary direct-relation matrix is in the first step. Experts provides the pairwise comparisons between the criteria of the system by the scores ranging from 0 to 4, indicating 0 for “no impacts” to 4 for “very high impacts”. A primary direct-relation matrix can be established through pairwise comparisons regarding the impacts as well as directions among criteria. An instance of an influence map can be observed in Figure 4 according to which the strength of the impact ranges from 0 to 4. In this stage, for n criteria, an initial matrix A = [aij] (aij denotes direct influence of factor i on factor j) is obtained using the pairwise comparisons.

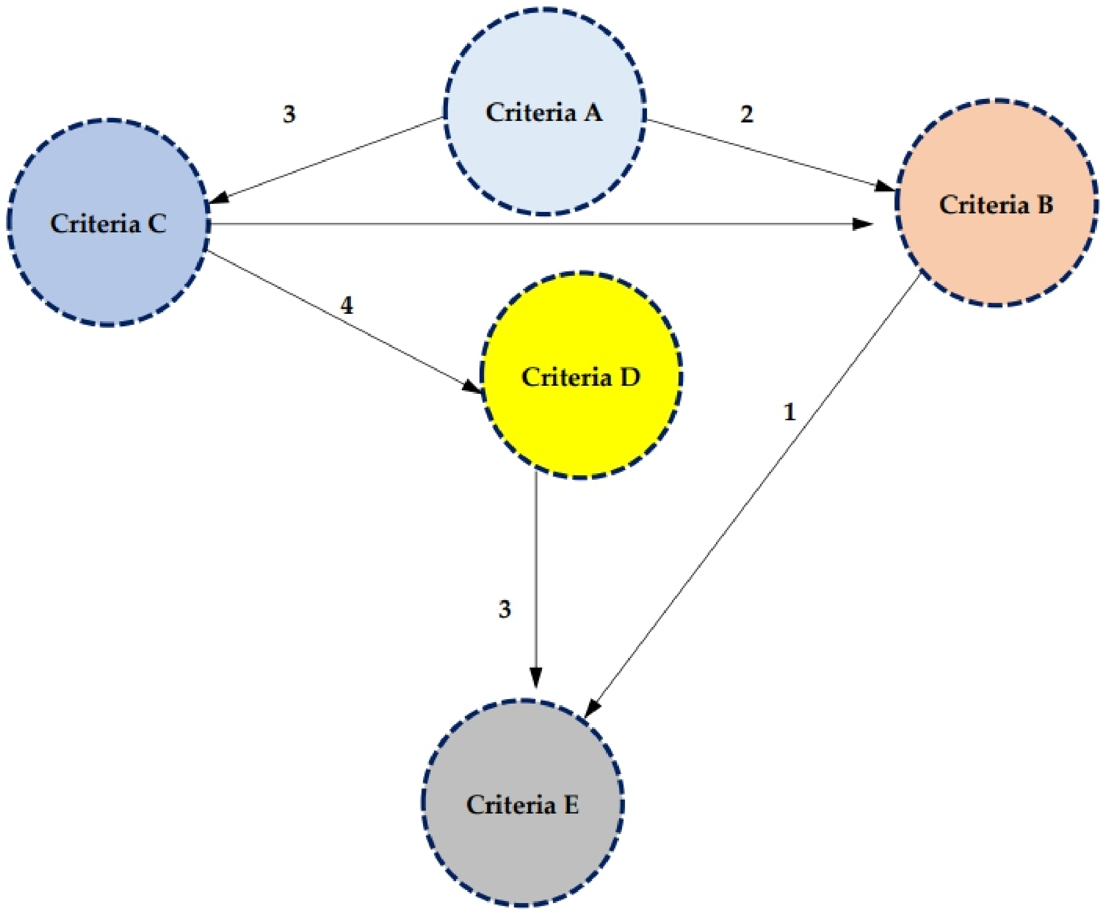


Figure 4. Example of an influence map.

Stage 2: In this step, normalization is done for the direct-relation matrix. The normalized directrelation matrix X can be acquired using Eqs 1 and 2, according to which all major diagonal elements will be zero.

$$X = y.A \quad (1)$$

$$y = \underbrace{\min}_{i,j}\left[\frac{1}{\max_{1\leq i\leq n}\sum_j^n a_{ij}}, \frac{1}{\max_{1\leq i\leq n}\sum_i^n a_{ij}}\right] \quad (2)$$

Stage 3: In this step, DEMATEL obtains the total-relation matrix. After obtaining the normalized direct-relation matrix, T which is the total-relation matrix is achieved through the following equation:

$$T = X(I - X)^{-1} \quad (3)$$

Where identity matrix is indicated by I.

Stage 4: In this step, the row and column overall values of T can be obtained as column vectors r and s correspondingly:

$$T = [t_{ij}]_{n\times n} \qquad i, j = 1,2, \dots, n \quad (4)$$

$$r_i = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1} \qquad i = 1,2, \dots, n \quad (5)$$

$$s_j = \left[\sum_{i=1}^{n} t_{ij}\right]'_{1\times n} \qquad j = 1,2, \dots, n \quad (6)$$

Where the superscript ′ represents transpose. (ri + si) forms an indicator of the influence strength given and taken, which means that (ri + si) represents the level of the overall impacts that factor i may have in the system. Thus, if (ri − si) has a positive value, subsequently, factor I will have a net impact on the other factors, and if (ri − si) has a negative value, then factor i will be totally under the influence of the other factors.

5. Method Evaluation

5.1. DEMATEL

A questionnaire survey was utilized in the present study for data collection. Data were gathered from 180 respondents in the universities who have had experience in the area of the supply chain in industries. They have worked in the private and public universities in the centers and departments of transportation and logistics, and sustainability and environment. Table 3 provides a breakdown of demographic information about the survey respondents. The majority of the respondents were male (57.22%) and held a PhD degree (80.56%). In terms of employment status, a significant portion were full-time employees (91.67%). Regarding age distribution, the largest group fell within the 30–40 age range (43.89%), followed by 41–50 (22.78%), and over 50 (27.22%). The respondents belonged to various faculties, with transportation and logistics (43.33%) and environmental sustainability (37.22%) being the most represented. Faculty ranks varied, with associate professors (46.67%) making up the largest group. Work experience in the industry was diverse, with the majority having 1–3 years of experience (49.44%). Furthermore, the majority of the respondents have worked in the industry for 1–3 years of experience (49.44%). Furthermore, the majority of the respondents have worked in the industry for 1–3 years. Reliability (C1), Responsiveness (C2), and Agility (C3) were chosen as the primary performance features, while Perfect Order Fulfillment (C1.1), Order Fulfillment Cycle Time (C2.1), Upside Supply Chain Flexibility (C3.1), Supply Chain Upside Adaptability (C3.2), Supply Chain Downside Adaptability (C3.3), as well as Overall value at risk (C3.4) have been chosen as the first level indicators for measurement of EV supply chain performance. DEMATEL aimed at determining the network associations of the criteria affecting each other. Influencing associations were found through questionnaires provided for every expert to rank each criterion regarding the suitable vendor on a 4-point scale at a range of 0–4, in which zero indicated "no influence" and four indicated "very high influence" correspondingly. Development of the questionnaire took place according to the pairwise comparison, based on which every question includes a pairwise comparison of two criteria. The experts had to score the intensity of the corresponding significance of the two criteria in every pairwise comparison.As shown in Table 4, the average initial direct matrix A is determined. We then calculated the normalized initial direct-relation matrix D. Then, Eq 4 was used to derive the overall relation matrix T as indicated in Table 5. The overall sum of the effects given to and taken from every criterion can be observed in Table 6 with the use of Eqs 5 and 6.

Table 3. Demographic information of the respondents.

Item	Value	Frequency	%
Gender	Male	103	57.22
	Female	77	42.78
Education	PhD	145	80.56
	Master	35	19.44
Employment Status	Full Time	165	91.67
	Part Time	15	8.33
Age	<30	11	6.11
	30–40	79	43.89
	41–50	41	22.78
	>50	49	27.22
Faculty	Transportation and logistics	78	43.33
	Environmental Sustainability	67	37.22
	Business School	14	7.78
	Industrial Engineering	21	11.67
Faculty Rank	Lecturer	23	12.78
	Assistant Professor	37	20.56
	Associate Professor	84	46.67
	Professor	36	20.00
Work Experience in Industry	<1 year	67	37.22
	1–3 years	89	49.44
	4–6 years	14	7.78
	7–9 years	7	3.89
	>9 years	3	1.67

Table 4. Initial direct matrix A.

Criteria	Reliability	Responsiveness	Agility
Reliability	0.00	3.30	3.80
Responsiveness	3.70	0.00	3.60
Agility	1.80	1.80	0.00

Table 5. Total influential relation matrix T.

Criteria	Reliability	Responsiveness	Agility
Reliability	1.11	1.36	1.75
Responsiveness	1.48	1.09	1.78
Agility	0.87	0.84	0.86

Table 6. Sum of influences given and received on each criterion.

Criteria	r_i	s_i	$r_i + s_i$	$r_i - s_i$
Reliability	4.22	3.46	7.67	0.76
Responsiveness	4.34	3.29	7.64	1.05
Agility	2.57	4.38	6.95	-1.81

A limit of 1.24 has been selected by the participating experts to establish a suitable Network Relationship Map (NRM). The results of the NRM of the DEMATEL method are presented in Figure5. In Figure 5, we also present the impact-direction map which provides valuable cues for accurate SC assessment. From the network relationship map of SC performance indicators, it is found that reliability is more important compared with responsiveness and agility. In addition, it is found that agility always receives impacts of responsiveness (T=0.1.36) and reliability (T=1.75).

5.2. CART and fuzzy logic results

DEMATEL was employed to identify the weights of SC performance indicators. In the next step, CART has been employed to identify the associations of the factors and performance of the supply chain. This way, we would be capable of generating linguistic decision rules that are conveniently understandable to be used in making decisions. CART was capable of solving the problem of finding rules in fuzzy rule-based techniques with no human intervention in the present study. This technique is beneficial because of its potential to generate decision rules automatically in the form of "IF-THEN". Given the primary objective of the present study to identify the significance level of performance indicators in SCORE influencing the SC performance, the application of CART was beneficial due to difficulties in the manual generation of the decision rules from the gathered data. Later, the development of the system based on fuzzy rules was carried out using the discovered decision rules. It should be noted that this system worked according to the rules found through the CART technique because learning from the data was impossible. Then, the 5-Likert numerical data were changed into linguistic variables of "Very Low", "Low", "Moderate", "High", and "Very High" to assist CART in finding the decision rules. The obtained decision rules were subsequently employed in systems working based on fuzzy rules. Triangular membership functions were used for the implementation of the fuzzy rule-based system. This kind of membership function with "Very Low", "Low", "Moderate", "High", and "Very High" linguistic variables were taken into account for every variable.

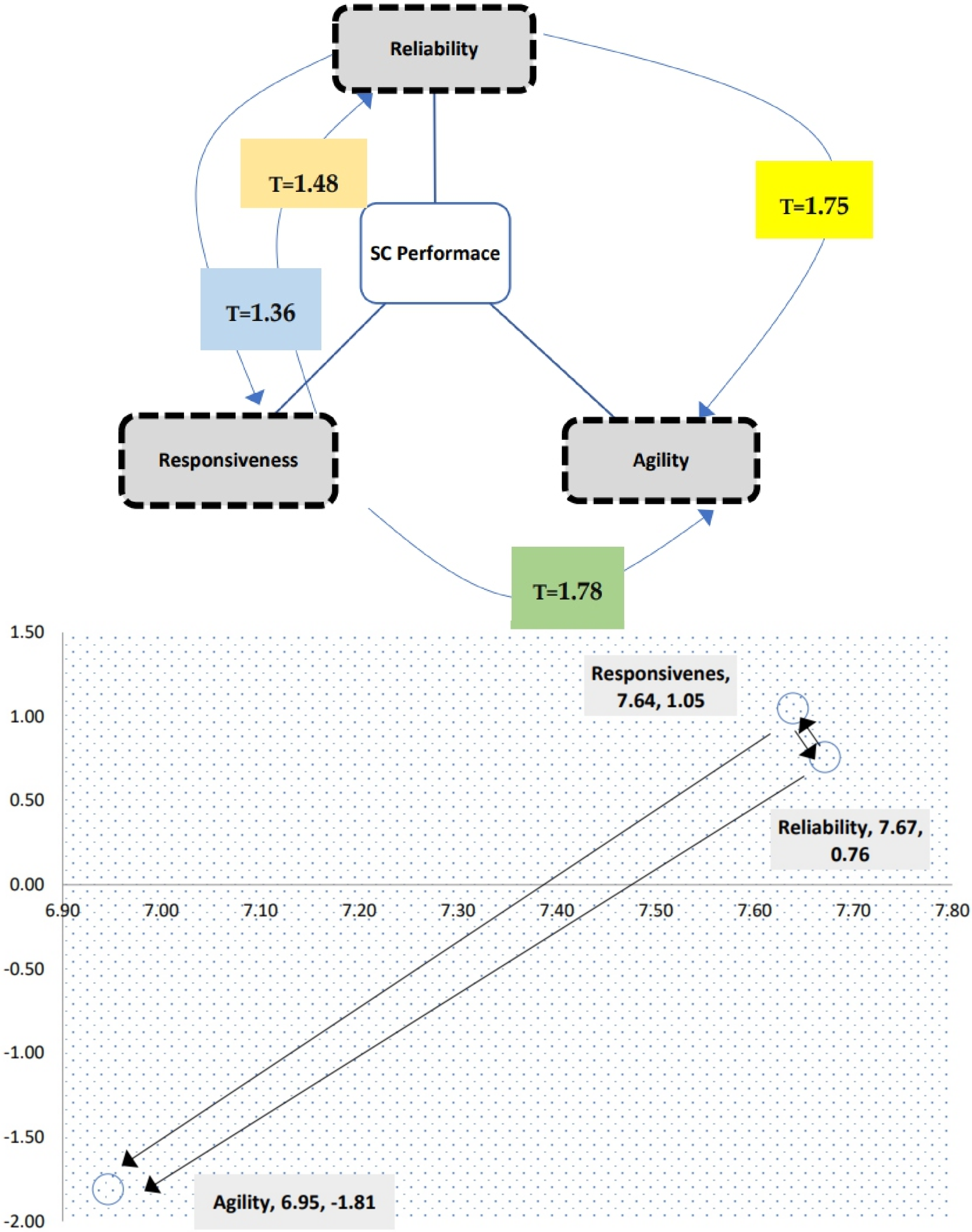


Figure 5. Network relationship map of SC performance indicators.

To better discover the decision trees, a clustering method was applied to the collected data. We used k-means for this task. We set k=3 to generate three clusters from the data. In Figure 6, the clusters are visualized versus the indicators and SC performance. In addition, the correlation of each performance indicator and SC performance is shown in Figure 7. Table 1 in Appendix A presents several decision rules which represent the exact associations of the SC performance and SCOR mode indicators in three generated clusters. As an instance, it is understood from the first rule that with [moderate] Reliability, [high] Responsiveness, and [high] Agility, a high-performance level would result. Moreover, the significance of every factor in every rule can be found from these rules. As an instance in the rule mentioned above, according to the experts' opinions, if Reliability, Responsiveness, and Agility in the EV supply chain are at a high level, it is possible to achieve a higher level of performance. These rules have the capability of being conveniently understood because they have been provided in linguistic forms. As a result, they are employed in fuzzy systems to design a system based on knowledge and indicate the role of every indicator in the performance of the supply chain in EVs industries. It is worth noting that timely improvement of systems that are based on knowledge is possible when novel data from new participants can be accessible since the rules produced by CART will be updated using the fresh data.

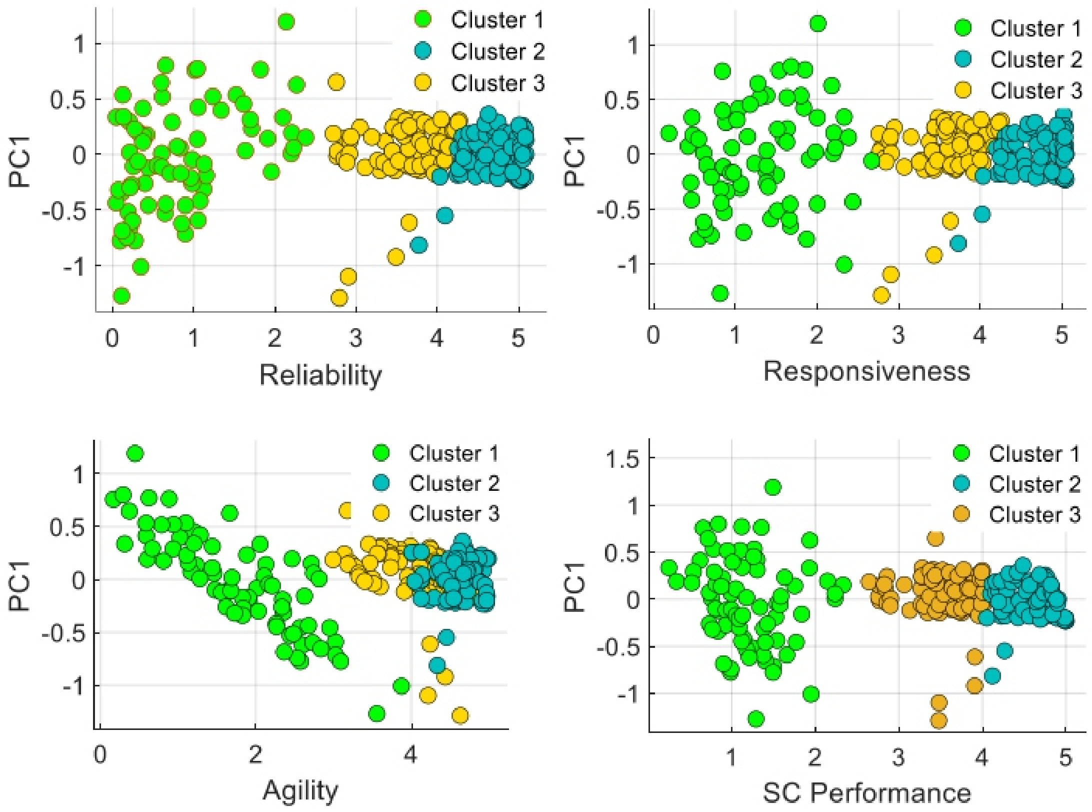


Figure 6. Clusters generated by k-means for supply chain evaluation.

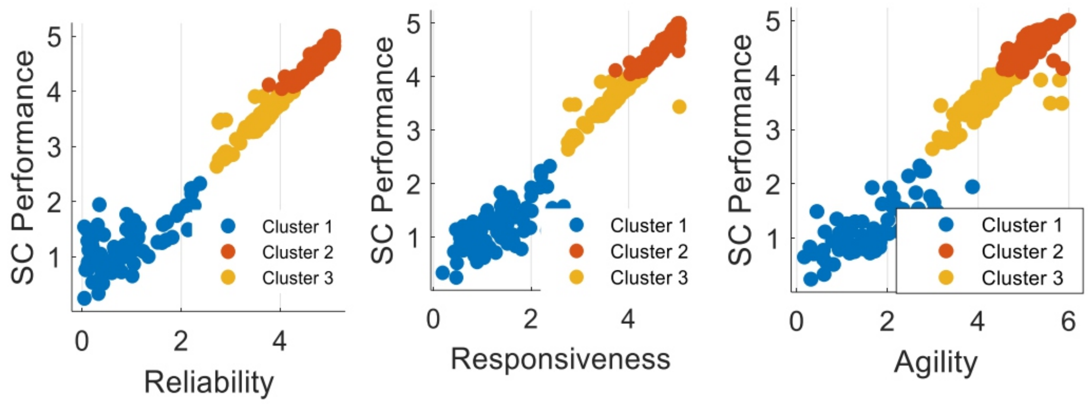


Figure 7. Correlation between the performance indicators and SC performance.

The fuzzy system was implemented in the fuzzy logic toolbox of Matlab software (see Figure 8). According to the discovered rules by CART, a fuzzy system based on rules was designed to identify the effect of different indicators on the performance of the EV supply chain. The FIS models are used to predict the impacts of SCOR indicators on the performance of the supply chain. Prediction of Reliability (C1), Responsiveness (C2) as well as Agility (C3) by the first level indicators of Perfect Order Fulfillment (C1.1), Order Fulfillment Cycle Time (C2.1), Upside Supply Chain Flexibility (C3.1), Supply Chain Upside Adaptability (C3.2), Supply Chain Downside Adaptability (C3.3), andOverall value at risk (C3.4) is performed in the FIS 1-3. Then, the last FIS aims at predicting the performance of the supply chain by Reliability (C1), Responsiveness (C2) as well as Agility (C3) (see Figure 8).

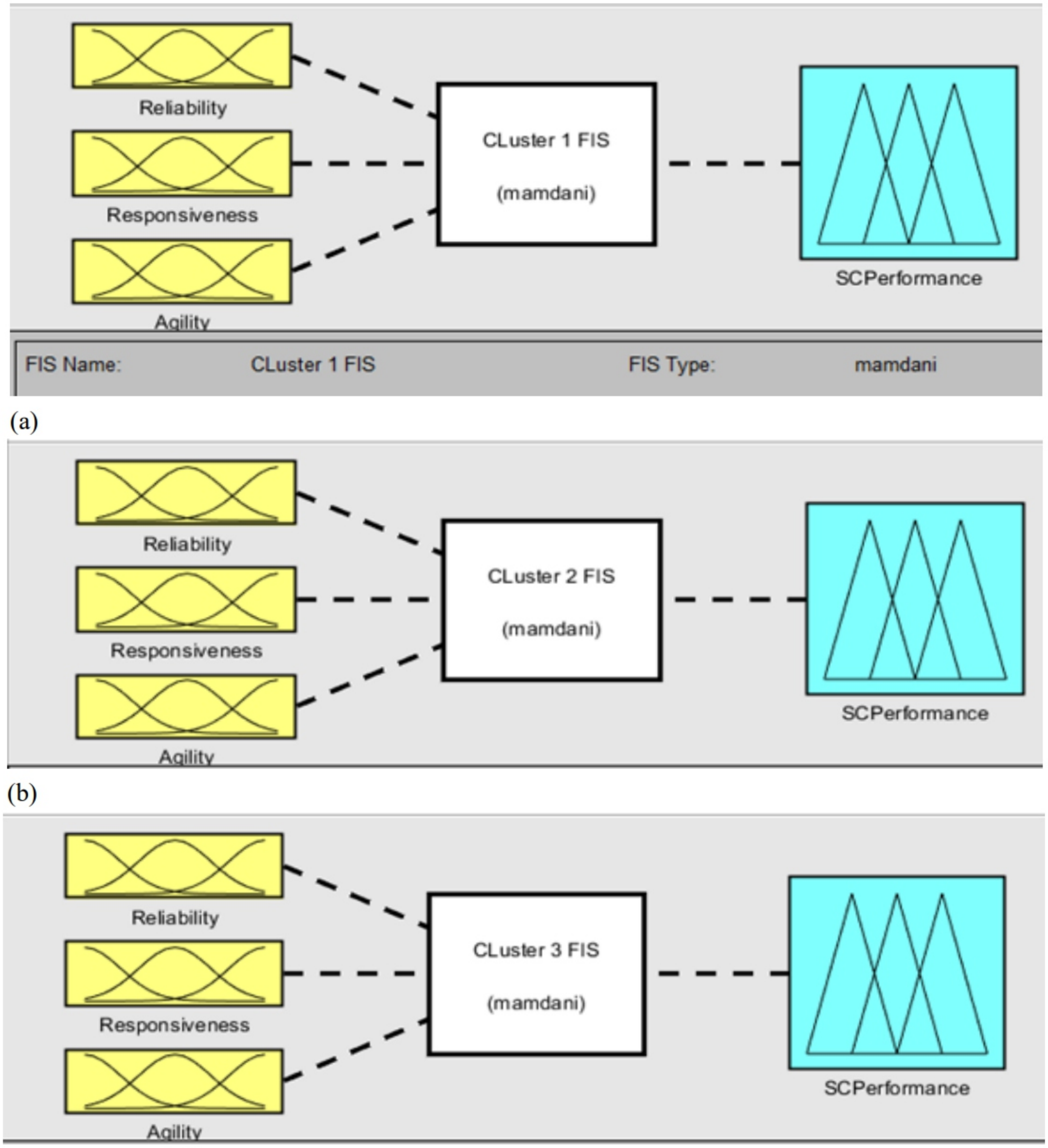


Figure 8. Fuzzy inference systems in (a) Cluster 1, (b) Cluster 2 and (c) Cluster 3.

We used Triangular membership functions in every FIS (see Figure 9). The mentioned kind of membership function is broadly utilized to design decision-making models through fuzzy logic techniques. Five linguistic variables have been considered for every factor in the FIS membership functions, including Very Low, Low, Moderate High, and Very High.

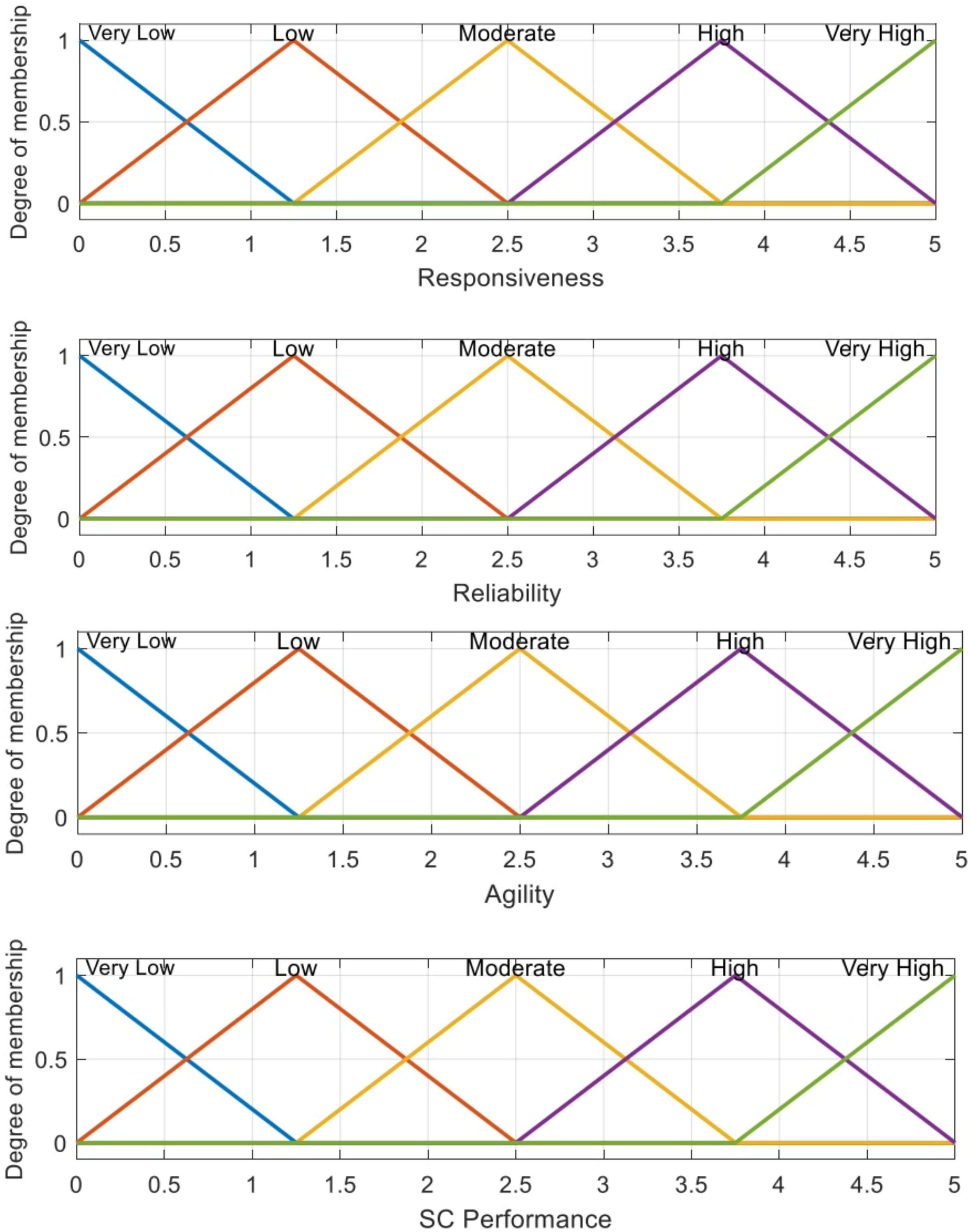


Figure 9. Membership functions in fuzzy inference systems.

Figure 10 indicates what was obtained from the FRB method in plots that can illustrate the contribution of individual indicators in the performance of the supply chain. Moreover, the corresponding significance of each indicator is better identified using these plots. This is possible through the incorporation of the identified fuzzy rules into the systems working based on fuzzy rules. Besides, the associations of the indicators and the system's behavior can be found according to the role of every two performance indicators of the model. It should be noted that the behavior of the fuzzy inferences system according to the produced fuzzy rules by CART and the input as well as output parameters can be observed through colors in the surface plots. The factors' significance level is represented in the surface plots (see Figure 10). The rule editor has been presented in Figure 11 for the systems implemented based on the rules. In addition, Figure 11 presents the prediction of SC performance in a fuzzy inference system through discovered rules.

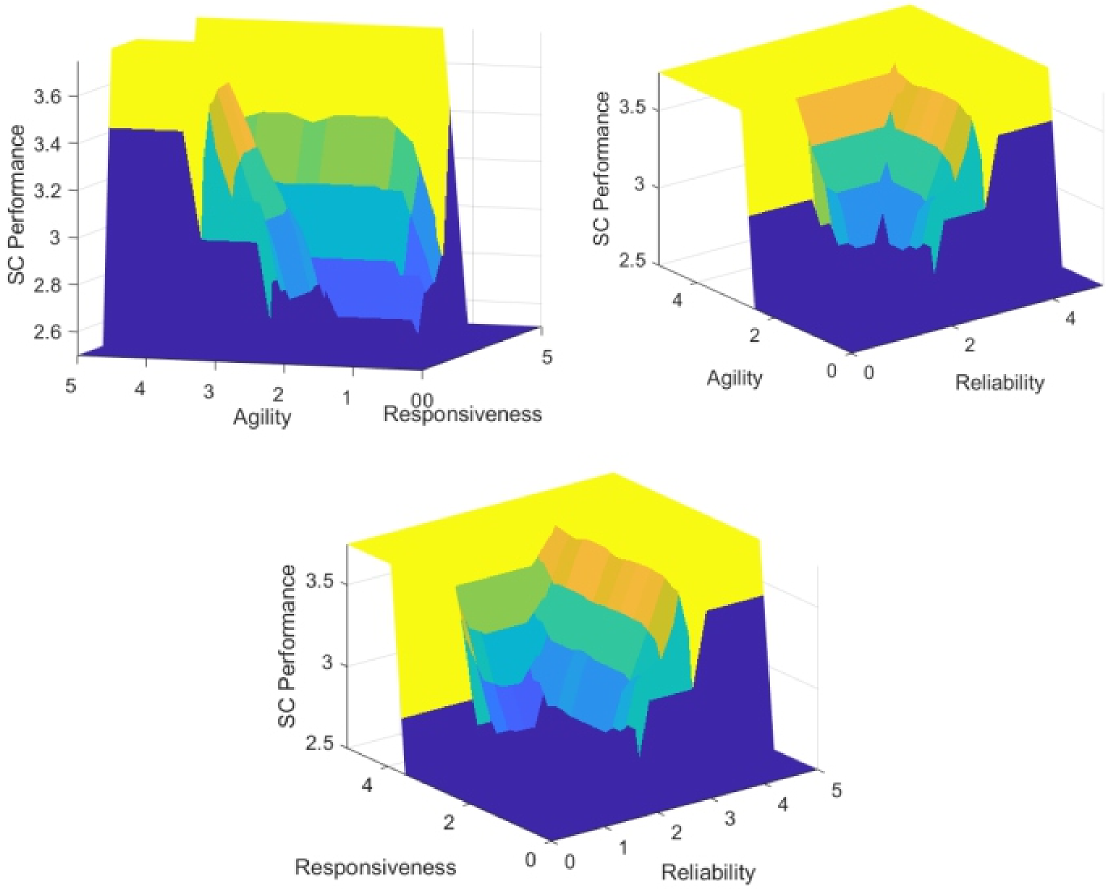


Figure 10. SC performance as a function of reliability, responsiveness and agility in fuzzy inference system.

Figure 11. Prediction of SC performance in fuzzy inference system.

5.3. Method evaluation

Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) to evaluate the proposed method [54]. MAE is defined as:

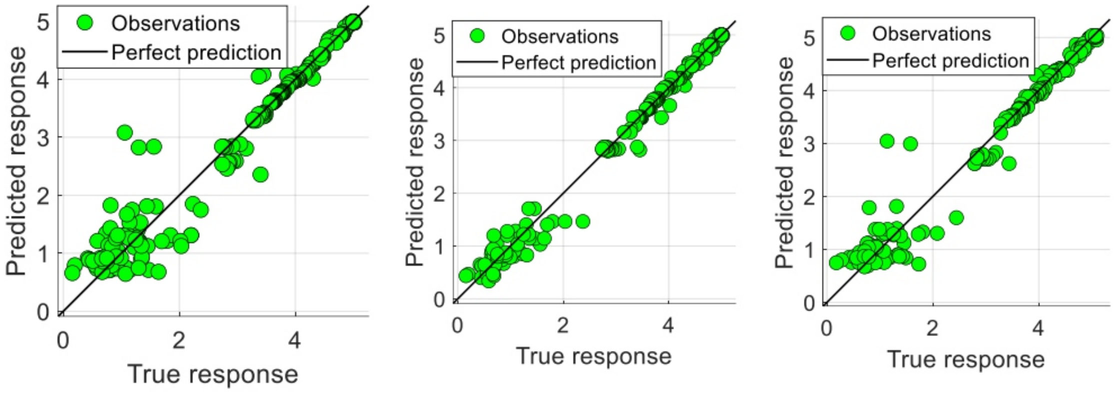
$$\mathrm{MAE} = \frac{\sum |a_i - \hat{p}_i|}{n} \tag{7}$$

Where ai is the actual value of SC performance, p̂i is the predicted value of SC performance, and n is the number of samples in each cluster. RMSE is defined as:

$$\mathrm{RMSE} = \sqrt{\frac{\sum |a_i - \hat{p}_i|^2}{n}} \tag{8}$$

To assess the accuracy of fuzzy rule-based models, we used the coefficient of determination ®2). The higher R2and smaller MAE and RMSE are, the better performance is. The results of R2and MAE and RMSE are presented in Figure 12. It found that the proposed method has predicted accurately the SC performance in three clusters (Cluster 1: R2=0.952, RMSE=0.333, MAE=0.178; Cluster 2:

R2=0.971, RMSE=0.168, MAE=0.103; Cluster 3: R2=0.964, RMSE=0.268, MAE=0.163) through the fuzzy rules in the fuzzy inference system.



R^2=0.952
RMSE=0.333
MAE=0.178

R^2=0.971
RMSE=0.168
MAE=0.103

R^2=0.964
RMSE=0.268
MAE=0.163

Figure 12. The evaluation results of SC performance in the fuzzy inference system.

We also compared the proposed method with other prediction learning techniques. The results of our comparisons with Support Vector Regression (SVR) [55], Multiple Linear Regression (MLR), Neural Network (NN) [41], and Adaptive Neuro-Fuzzy Inference System (ANFIS) [56–59] are presented in Table 7. Overall, the results reveal that the proposed method which combines clustering, decision trees, and fuzzy rule-based techniques outperform the other techniques in terms of RMSE, MAE and R2.

Table 7. Methods comparisons.

Method	RMSE	MAE	R^2
Proposed Method	0.245	0.127	0.965
ANFIS	0.382	0.158	0.942
NN	0.475	0.357	0.895
MLR	0.492	0.368	0.876
SVR	0.371	0.149	0.953

6. Research implications

Electric vehicles are crucial for addressing environmental issues like air pollution and climate change [60,61]. They produce fewer emissions than traditional internal combustion engine vehicles, leading to cleaner air and more sustainable development. Electric vehicles help the country become less dependent on foreign oil by reducing the demand for gasoline. Manufacturing, charging infrastructure, and renewable energy are just a few of the industries that benefit from the booming EV market. Electric vehicles benefit public health because they reduce exposure to noise and air pollution. They provide low-cost, dependable transportation options, which are especially useful in crowded, polluted cities.

In supply chain context, numerous performance measurement models have been developed; however, a performance measurement model based on indicators of customer perceived value (Reliability, Responsiveness, and Agility) in the SCOR model has not been created specifically for the EV supply chain. Customer perceived value, which represents the customer's perception of the benefits and costs associated with a transportation service, holds significant importance in the field of transportation. It plays a crucial role in determining customer satisfaction and loyalty. Moreover, customer feedback should be continuously monitored and analyzed by transportation providers to identify areas for improvement and make necessary adjustments to their services. This approach helps in maintaining high levels of customer perceived value, which is crucial for long-term success in the transportation industry. Additionally, a high level of customer perceived value can foster improved collaboration and communication within the supply chain. When customers perceive that the supply chain delivers high-quality products or services, they are more inclined to engage with the supply chain, provide feedback, and thereby assist the supply chain in identifying areas for improvement and optimizing its operations accordingly. In summary, we found that reliability, responsiveness, and agility are critical characteristics of a successful supply chain in EV. A reliable supply chain ensures consistent delivery of products or services, a responsive supply chain quickly adapts to changing customer needs and market conditions, and an agile supply chain quickly and efficiently responds to supply chain disruptions. By focusing on these characteristics, companies can build more effective and efficient supply chains that meet customer needs and drive business success.In case of methodology used in this work, a new method was developed in the context of supply chain assessment. The fuzzy logic approach was implemented in this study using decision trees. In transportation studies, the technique of decision trees had been widely employed for prediction tasks. The CART approach was used to automatically discover the decision rules for SC performance evaluation from the data. These rules were then employed in the fuzzy logic approach to identify the associations between the input and output variables, eliminating the need for manual parameterization of variables and decision rules. This characteristic of the suggested method could be considered a positive aspect compared to approaches that relied solely on fuzzy inference, as the definition of appropriate linguistic terms and relative fuzzy numbers could present a significant weakness in such systems. Moreover, the number of indicators and linguistic terms could result in the exponential growth of decision rules, making the design of the rule base system more complicated. Therefore, the adjustment of the inference system was perceived as a learning process involving a team of experts in the area of SC performance and fuzzy inference in real-world applications.

7. Conclusions

We strived to introduce a new model based on the SCOR model to measure the performance of the EV supply chain by employing multi-criteria decision-making as well as machine learning techniques. The proposed assessment method was based on DEMATEL, CART and FIS for revealing the significance level of SCOR indicators in EV supply chain. Despite prior method that was merely dependent on FIS, the present work combined multi-criteria decision-making and machine learning to evaluate the performance of the supply chain in the EV supply chain using the SCOR model. The use of CART with the aid of the clustering technique was effective in discovering decision rules from the collected data. According to the discovered fuzzy rules, several fuzzy inference systems were developed and evaluated for the assessment of SC performance. The results confirmed, the reliability performance criteria in the SCOR model have the highest level of importance for SC performance in the EV supply chain compared with the other criteria, responsiveness, and agility. Overall, we found that the employment of a predictive model according to fuzzy logic and the SCOR model is practical in the prediction of SC performance in the EV context. Although the proposed method has effectively predicted the SC performance, there are several limitations that must be considered in future works. First, the proposed method used the CART approach to discover the decision rules from the data. This technique can be optimized using optimization machine learning techniques to better discover the decision rules. In addition, the incorporation of other learning strategies such as ANFIS with the aid of incremental approaches can be effective in the training of the system for large datasets for the evaluation of SC performance. Furthermore, this study can be further developed for the fuzzy MCDM techniques which have been more effective compared with the crisp-based MCDM techniques in the evaluation of criteria of decision-making systems. Moreover, statistical methods, such as Partial Least Squares Structural Equation Modeling (PLS-SEM), are suggested for the development of hypothetical models in combination with the proposed method for assessing factors in the improvement of the EV supply chain.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflicts of interest

The authors declare no conflicts of interest.

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Endolithic microbes may alter the carbon profile of concrete

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A B S T R A C T

There is great interest to understand and reduce the massive carbon footprint of the concrete industry. Recent descriptions of microbes incidentally living inside concrete materials ("concrete endoliths") raised questions about how much carbon is either stored in or released from concrete by these microbes. We generated preliminary global estimates of how much organic carbon is stored within the living biomass of concrete endoliths (biomass-carbon) and much CO2 is released from respiring concrete endoliths. Between 2020–2022, we collected widely varying samples of Portland cement-based concrete from Lubbock, Texas. After quantifying endolith DNA from 25 concrete samples and estimating the current global mass of concrete, we calculated that the global concrete endolith biomass-carbon as low as 5191.9 metric tons (suggesting that endoliths are a negligible part of concrete's carbon profile) or as high as 1141542.3 tons (suggesting that concrete endoliths are a pool of carbon that could equal or offset some smaller sources of concrete-related carbon emissions). Additionally, we incubated concrete samples in air-tight microcosms and measured changes in the Co2concentrations within those microcosms. Two out of the ten analyzed samples emitted small amounts of CO2 due to the endoliths. Thus, "concrete respiration" is possible, at least from concrete materials with abundant endolithic microbes. However, the remaining samples showed no reliable respiration signals, indicating that concrete structures often do not harbor enough metabolically active endoliths to cause CO2 emissions. These results are preliminary but show that endoliths may alter the carbon dynamics of solid concrete and, thus, the carbon footprint of the concrete industry.

Keywords: cement; carbon footprint; carbon storage; respiration; biomass; industrial ecology

1. Introduction

1.1. The popularity and ubiquity of concrete

Built environments such as cities and towns have rapidly expanded around the world since the 1950s, and concrete has emerged as the primary building material [1]. Now, concrete is the most abundant human-made material on Earth and a symbol of urbanization and modernity [2]. The total quantity of concrete worldwide cannot be directly ascertained (see Section 4.2); however, in 2020, it was estimated to be around 549 Gt, which is about half the dry weight of the Earth's living biomass [3].

This is astounding but unsurprising given that concrete production ranges from 20–30 Gt year-1, which is much higher than the production rates of brick, asphalt, metals, plastics, and wood [4].

Concrete is popular because of its low cost, desirable mechanical properties, incredible versatility, and wide availability [5]. It is a composite material that can be modified and innovated upon to suit numerous applications [6]. The base materials include aggregate (usually sand and/or gravel which act as fillers and strength enhancers), cement (which eventually binds the aggregates together into solid structures), and water (which activates the cement's binding activity). The source, composition, proportion, and treatment of these ingredients widely varies, and these variations affect the workability, durability, and strength [7]. Concrete structures can be modified further by adding additional ingredients, performing mechanical treatments, and incorporating reinforcement elements. Concrete is used in various construction projects, poured on-site and pre-cast, dispensed by hand and with machinery, and placed in a wide variety of environments, including belowground and underwater. Unrivaled popularity, high production rates, and slow decomposition rates have made concrete a substantial part of the biosphere. Yet, while the utility of concrete is undeniable, it has several drawbacks.

1.2. The carbon footprint of concrete is its greatest drawback

Concrete has some undesirable mechanical properties, unique maintenance issues, problematic landscape functions, and negative aesthetic issues [8–10]; moreover, concrete has been most heavily scrutinized for its carbon profile. Many industrial life-cycle analyses show that the production and use of concrete generates between 5–10% of global greenhouse gas emissions [11,12]. Yet, concrete has some of the lowest embodied CO2 ratings of all construction materials, around 0.06–0.2 (meaning that 0.06–0.2 kg of CO2 is produced for every kg of concrete [13]). Much of the emissions associated with concrete are generated during the manufacture of one of concrete's basic ingredients: cement.

Ordinary Portland cement, the most popular type of cement, is typically manufactured by burning fossil fuels (often coal) to superheat raw minerals (mostly limestone and clay) in large kilns. The heating induces calcination reactions, which transform the minerals into the precursor material of cement and release CO2 as a byproduct. This pushes the embodied CO2 value for Portland cement alone to around 1 [14]. This is alarming, especially in the context of climate change; however, the embodied CO2 values of cement are still low compared to materials such as steel (0.4–6) and plastics (2–10) [13]. Furthermore, blending the cement with substances that have less embodied CO2 (e.g., coal fly ash, iron slag) further reduces the embodied CO2 of the final mixture [14]. In the end, the embodied CO2 of concrete or cement does not fully explain the massive carbon emissions attributed to these industries (which have been recently emitting around 3 billion metric tons of CO2 per year [15]). Those emissions problems are better understood as a result of incredibly high production rates [13], that is, the emissions problems are directly tied to concrete's popularity and ubiquity.

The widespread recognition of concrete's massive carbon footprint has initiated a great deal of research. Much of this research has focused on cataloging the various carbon fluxes associated with concrete, from cradle to grave. We now know that carbon is released at many points throughout concrete's lifecycle [16] and that carbon is absorbed by solid concrete via carbonation (the gradual process by which CO2 migrates into concrete structures and reacts with the certain constituents of cement to form carbonate minerals). The long-term structural effects of carbonation are usually undesirable; however, in terms of carbon dynamics, carbonation represents a significant sequestration of atmospheric carbon into a highly stable mineral form [17]. The extent to which any concrete structure becomes carbonated depends on many factors, including the cement type, the structure shape, environmental conditions, and time [18]; moreover, this process may reabsorb between 7–57% of the CO2 emitted while making the necessary cement [19,20]. Carbonation is also conceptually important because it demonstrates that solidified concrete is not completely static or inert but instead is a dynamic system with cryptic properties.

1.3. Microbes may alter the carbon dynamics of rocks such as concrete

The fact that concrete structures are dynamic systems capable of chemistry-driven carbon flux (carbonation) raises questions about the possibilities of biology-driven carbon flux in concrete. This possibility is strengthened by relatively recent discoveries of microbes that live in and on concrete (e.g., [21]). While concrete seems an unlikely habitat, it is essentially synthetic rock, and it has long been known that microbes utilize natural rocks as habitats. The microbes that specifically live insiderocks are called endoliths [22]. The endolithic niche is interesting because it means that entire volumes of rocks (including concrete) are potential habitats for certain microbes, which, in turn, means that the inner volumes of rocks may be harboring carbon cycling ecosystems.

Endolithic microbial ecosystems are often sparse because life inside solid rock is often constrained by several factors, most notably the lack of light, nutrients, moisture, and space. Subsequently, endolithic systems generally contain little biomass and support little biological activity [23]. That said, levels of endolithy vary considerably among the wide variety of rocks and lithic formations found on Earth. Some endolithic communities beneath the ocean floor have cell densities as low or lower than 104 cell g-1 material [24,25], while some coral substrates hold over 100 mg of endolithic biomass per cubic centimeter [26] and some surface rock formations can hold up to 14 g of dry endolithic biomass per square meter [27]. Direct measures of carbon cycling and indirect measures of growth show that these organisms can incorporate and release carbon on either extremely slow, almost geological timescales (every 103–104 years) or on much more rapid decadal timescales [28,29]. Yet, as with concrete, appreciating the global carbon profile of endolithic microbes is primarily an issue of scale. Even if most rock material harbors only trace levels of endoliths, endolithic biomass and activity becomes significant when multiplied by the total volume of the potential endolithic habitat, which encompasses the top several kilometers of the Earth's crust (i.e., the upper geosphere, which is much more voluminous than the hydrosphere and pedosphere [30]).

The Earth's rock materials are increasingly being transferred into the novel rock type we call concrete; therefore, it is becoming important to study if and how endoliths utilize concrete. To date, few studies have documented the naturally occurring endoliths that inhabit ordinary concrete. It is
currently known that microbial communities within concrete (in "endo-concrete" environments) can include bacteria, archaea, and fungi [31], with endo-concrete bacteria currently being the most well described and perhaps encompassing the most taxonomic diversity [21]. At least two endolithic subtypes have been noted in concrete - cryptoendoliths (which were likely present in the original concrete ingredients, and then were entrapped in the solidified concrete [32]) and euendoliths (which colonize concrete from the outside by actively boring tunnels into the substrate [33]).

While perhaps less active and dynamic than other microbiomes, endo-concrete communities are not static and are subject to compositional shifts over time [32,34]. Furthermore, concrete endolith communities may be as variable as the concrete structures they inhabit, ranging from barely detectable in some concrete structures to surprisingly rich in other samples [31]. Across samples, communitylevel variables such as endolith viability and abundance often correlate with the basic physicochemical features of the concrete samples, with lower concrete alkalinities and densities seeming to favor the establishment of endoliths [31]. These incidental concrete endoliths are distinct from intentionalconcrete endoliths (which are seeded into experimental types of self-repairing concrete; see [35]). Given that concrete's role in the global environment is inextricably tied to carbon, it is fitting to study how widespread incidental endoliths might alter the carbon profile and carbon dynamics of concrete. As with the endoliths that inhabit natural rock formations, concrete endoliths represent quantities of organic matter and organic carbon. As viable organisms, concrete endoliths also represent the potential for microbially-driven carbon flux in or out of the concrete. Additionally, once again, determining if this facet of concrete is significant depends on scaling the findings up to match the global quantities of concrete.

1.4. Study objectives

Our first objective was to estimate the global biomass of concrete endoliths. Previous studies have indicated that, on a per gram basis, concrete usually contains very low levels of microbial biomass and, therefore, low levels of organic carbon. Yet, because there are hundreds of gigatons of concrete on the planet, it is conceivable that concrete endolithic ecosystems add up to a sizable pool of biomass and carbon. Also, being endolithic microbes that can potentially utilize the entire volumes of their hostrock (as opposed to only the surfaces), concrete endolith biomass can be logically estimated from two currently obtainable pieces of data: the average concrete endolith biomass concentration (ng g-1concrete) and the global estimate of concrete mass (Gt). However, there is considerable imprecision surrounding our understanding of concrete endolith biomass concentrations and global concrete quantities; therefore, we set out to compile a set of estimates that use different parameters and then evaluate the practical significance of these estimated quantities.

Our second objective was to determine if the metabolic activity of endoliths causes concrete structures to emit carbon as CO2 gas. All cells, whether active or dormant, represent pools of organic carbon; however, only active cells produce CO2 as they metabolize and respire. Unlike biomass, gaseous CO2 can move and diffuse out of the system in which it was produced, and this can cause a system (including endo-concrete ecosystems) to release carbon. In a concrete structure, this biogenic release of carbon would occur relatively late in the concrete's lifecycle and would be in addition to carbon embodied in concrete during its production (Figure 1). Overall, concrete endolith respiration has the potential to enlarge the concrete's carbon footprint; therefore, we examined whether incidental concrete endolith communities release measurable amounts of carbon from their host concrete.

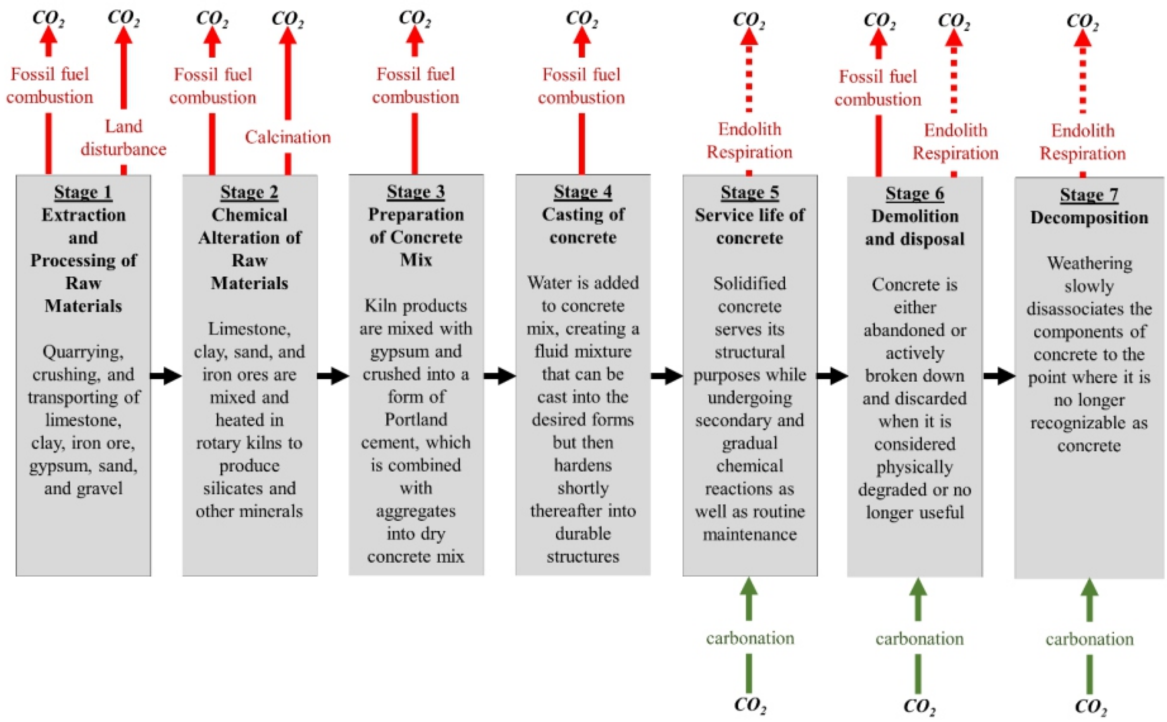

Figure 1. Typical life-cycle stages of Portland cement-based concrete with associated inputs and outputs of CO2-C. Stages 1–4 and 6 involve known processes of carbon release (solid red arrows). At stages 5–7, after concrete solidification, some carbon capture occurs (solid green arrows). Hypothesized processes of carbon release resulting from concrete microbes are shown at stages 5–7 (dashed red arrows). This figure incorporates elements from other concrete studies: [16,36].

2. Materials and methods

2.1. Concrete sample collection

We collected two sets of concrete samples: one set for the biomass measurements (Objective 1) and one for the respiration experiment (Objective 2). We collected the concrete samples designated for biomass measurements during a previous study on concrete endoliths, as described in detail in Brown et al. [31]. Briefly, we procured 25 independent samples from Lubbock, Texas, USA (33.5° N, 101.8° W, ~978 m elevation) between June-August 2022. This city is semi-arid with a mean annual precipitation of 485 mm and a mean annual temperature of 15 °C [37]. We gathered concrete of various types and from various settings: poured concrete left submerged underwater, belowground poured structures surrounded by soil, ground-level poured slabs with exposed top surfaces and bottom surfaces contacting the soil, aboveground poured structures with no direct contact to the ground, and pre-cast concrete masonry units (CMUs), otherwise called cinder blocks.

We collected the concrete samples for the respiration experiment during August-October 2020. However, these samples (n = 10) also came from the city of Lubbock and were a mix of submerged, belowground, ground-level, aboveground, and CMU samples (Table 1). Samples for both experiments were independent samples of "ordinary" concrete made with either Portland cement or a Portland cement blend. With permission, we collected samples that were abandoned, discarded, or leftover from demolition sites. Our bulk samples were between 10–25 kg with effective thicknesses of >60 mm, which enabled extraction of sub-samples of a sufficient size and quantity.

Table 1. Descriptions of ten concrete samples used for respiration analysis (Objective 2). Samples are sorted by the general type and source of concrete.

Sample ID	General type	Concrete sample description
R-Submrg-1	Submerged fragment (poured)	Fragment left underwater in a freshwater pond
R-Submrg-2	Submerged fragment (poured)	Remnant of an old footbridge in a perennial freshwater stream (with re-bar)
R-Blwgrnd-1	Belowground structure (poured)	Building footing excavated during a large-scale renovation (with re-bar)
R-Blwgrnd-2	Belowground structure (poured)	Post setting recently unearthed from an urban backyard
R-Ground-1	Ground-level slab (poured)	Sidewalk from within an apartment complex
R-Ground-2	Ground-level slab (poured)	Housing pad beneath a recently demolished house (with re-bar)
R-Abvgrnd-1	Aboveground structure (poured)	Indoor flooring from a multi-story commercial building (with re-bar)
R-Abvgrnd-2	Aboveground structure (poured)	Exposed flooring from the top story of a parking garage (with re-bar)
R-CMU-1	Aboveground CMU (pre-cast)	8-inch, 2-core cinder block left outside atop a pile of cinder blocks
R-CMU-2	Aboveground CMU (pre-cast)	4-inch, 3-core, hollow-style concrete block from an abandoned commercial building

Note: These samples are not the same samples used for microbial biomassing (Objective 1). Those are described in Brown et al. [31].

2.2. Extracting, cutting, and pulverizing of concrete sub-samples

We extracted sub-samples from each large bulk sample of concrete. For the concrete used for biomass measurements, the methods of sub-sample extraction and the procedures for cutting and pulverizing sub-samples are described in Brown et al. [31]; we prepared the sub-samples for the respiration analyses in the same manner. Briefly, we used a drill press to extract cylindrical sub-samples from the poured concrete bulk samples and a tile saw to extract cuboidal sub-samples from the CMU bulk samples. With a small tile saw, we removed the surface material from each concrete sub-sample to isolate the internal, endolithic material (which we defined as any internal material at least 5 mm from any surface of the original structure). The dimensions of the sub-samples were standardized as much as possible in terms of the shape and volume (55 cm3 ±1 cm3). We surface sterilized and aseptically pulverized all sub-samples using a custom-made, mortar-and-pestle-type instrument [31]. These preparation methods and instruments reflected the fact that our field samples were of various shapes and sizes, our laboratory analyses required certain sample manipulations and volumes, and contamination risks were high. To the extent possible, our final sets of concrete samples represented a wide variety of urban concrete structures, though they only included the material and microbes that had existed within these structures.

2.3. Extraction and quantification of microbial DNA

We estimated the endolithic biomass in 25 concrete samples by first measuring the concentrations of double-stranded DNA (dsDNA). We used each pulverized sub-sample from each bulk sample as an independent replicate. The DNA extractions are described in Brown et al. [31], but we mostly followed the protocol by Kiledal and Maresca [38]. Briefly, we treated 10 g of each pulverized sub-sample with a lysis solution containing 0.5 M EDTA, 20 mg/mL Proteinase K solution, 20% SDS, and acetic acid. We followed this with an extended 24-hr incubation at 55 °C and then high-speed agitation and centrifugation to isolate the supernatant. For solubilization and binding, we combined the supernatant with Qiagen Buffer QG amended with a 25 mM NaCl solution and Triton X-100, a 1-mg/mL yeast RNA solution, and silica. We washed the silica-bound DNA pellets in 80% ethanol and air-dried. We resuspended and eluted the pellets three times using 10 mM Tris. We standardized the DNA quantifications by using consistent concrete sample inputs (10.0 g) and consistent extract volumes (50 µL). From the fluorometric DNA concentration readings (ng of dsDNA µL-1 extract), we calculated the total DNA recovery per sample (ng) and the DNA concentration of the concrete sample (ng DNA g-1 concrete).

2.4. Estimations of microbial biomass

We estimated the global mass of concrete endoliths using several different parameters and combinations of parameters. For each estimate, we either used the mean DNA concentration (0.0283 µg g-1 concrete) or the median (0.0016) calculated from this study's concrete samples (n = 25). We separately converted the two DNA concentration averages to either the microbial biomass-carbon(Cmic; µg g-1 concrete) using one of five microbial DNA-to-biomass conversion factors (Table 2). These conversion factors were developed by correlating DNA concentrations of soil samples with more direct measures of Cmic. We used DNA-to-biomass conversion factors because other preexisting methods for directly measuring Cmic were not suitable for concrete samples; moreover, we used conversion factors designed for soil microbes because no conversion factors for endolithic microbes were available (see Section 4.2).

Table 2. Selected DNA-to-biomass conversion factors shown in ascending order along with source information. Sample DNA concentrations are multiplied by the conversion factor to obtain an estimate of sample Cmic concentrations.

DNA-to-biomass conversion factor	Source	Study system	Relationship coefficient between DNA and biomass measurements
4.41	Semenov et al. [39]	Alkaline and carbonate soils	$R^2 = 0.97$
5.0	Anderson and Martens [40]	Arable and forest soils	$R^2 = 0.95$
12.0	Fornasier et al. (*low*) [41]*	Acidic arable soil	$R = 0.96$**
38.11	Gong et al. [42]	Arid and semi-arid soils	$R = 0.99$
63.5	Fornasier et al. (*high*) [41]*	Sandy arable soil	$R = 0.96$**

* Fornasier et al. [41] reported a range of conversion factors of which we used the lowest (low) and highest (high) factor.
**Shown is the overall correlation coefficient reported by Fornasier et al. [41] for multiple study systems. Correlation coefficients for individual study systems were not reported.

After multiplying an average DNA concentration (µg g-1 concrete) by a conversion factor to produce an estimate of Cmic concentration (µg g-1 concrete), we multiplied each Cmic concentration by the global mass of concrete as of 2023, which we estimated by assuming that the global annual cement production was 4.1 Gt [43] and that cement is typically one-seventh of the total concrete mass [4,13,44], meaning that 28.7 Gt of concrete has been annually produced for the last several years. Elhacham et al. [3] estimated the global mass of concrete to be 549 Gt in 2020; therefore, adding three years' worth of concrete production (86.1 Gt) amounted to a current global quantity of 635.1 Gt or 6.351 × 1015 g. Then, we converted the global Cmic quantities to metric tons (megagrams) by dividing by a fixed value (Eq 1). Additionally, we calculated the total microbial biomass of concrete endoliths (in metric tons) by dividing the Cmic estimates by 0.46 (the assumed proportion of organic carbon in total microbial biomass [40]).

$$Global\ biomass = \frac{(DNA\ concentration \times Conversion\ factor) \times (6.351\ \times 10^{15})}{1\ \times\ 10^{12}} \quad (1)$$

2.5. Microbial respiration assays

We determined if CO2 was released from concrete by respiring endoliths by analyzing gaseous changes within air-tight microcosms loaded with concrete. From each bulk sample of concrete, we extracted four 55-cm3 sub-samples, which we aseptically pulverized for separate microcosms (Figure 2). Of the four sub-samples from a given bulk sample, we left two concrete sub-samples untreated ("fresh") and sterilized the other two sub-samples by autoclaving three times over five days. There is no established method of sterilizing concrete, but we partially validated this method with culture tests (culture plates inoculated with fresh endo-concrete consistently showed microbial growth within seven days, while plates inoculated with autoclaved concrete did not [31]). The sterilized sub-samples revealed whether concrete with no biological activity could cause gaseous changes within microcosms and prevented us from erroneously attributing abiotic gaseous changes to endolithic microbes.

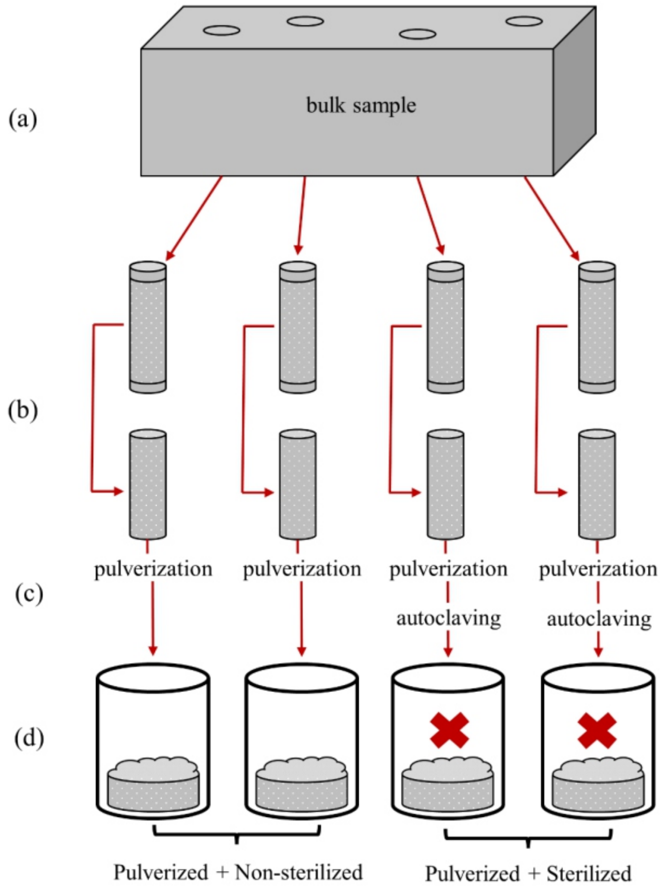

Figure 2. The extraction and treatment of concrete sub-samples used for respiration analysis. (a) From each bulk sample of concrete, we extracted four sub-samples, as cylindrical cores or cuboids. (b) We trimmed the surface portions off each sub-sample to isolate the endolithic portion. (c) We pulverized each sub-sample and autoclaved two of the four before (d) loading into microcosms.

We assembled the microcosms using 170-mL glass jars with modified twist-on metal lids (Figure 3). We fitted each plastisol-lined lid with one air inlet, one air outlet, and one septum. Each inlet was a nickel-plated brass bulkhead set into a 6.35-mm hole drilled into the outer edge of the lid. We placed metal and silicone washers between both bulkhead tightening nuts and the lid. We attached a 15-mm silicone tube (3.175 mm ID × 6.35 mm OD) to the bottom bulkhead barb to enhance air mixing in the microcosm. To the top bulkhead barb, we attached tubing, a female Luer lock (3.2 mm, polypropylene), a one-way stopcock valve (polycarbonate, female-to-male Luer lock), and a male Luer plug (polypropylene). We installed each outlet on the edge of the lid directly opposite of the inlet. The outlets were identical to the inlets except that these neither had tubing on the bottom bulkhead barb nor a stopcock valve. We drilled 10.6-mm holes into the center of each lid and inserted a 20-mm butyl rubber septum. We autoclaved and dried the partially assembled microcosms prior to sample loading.

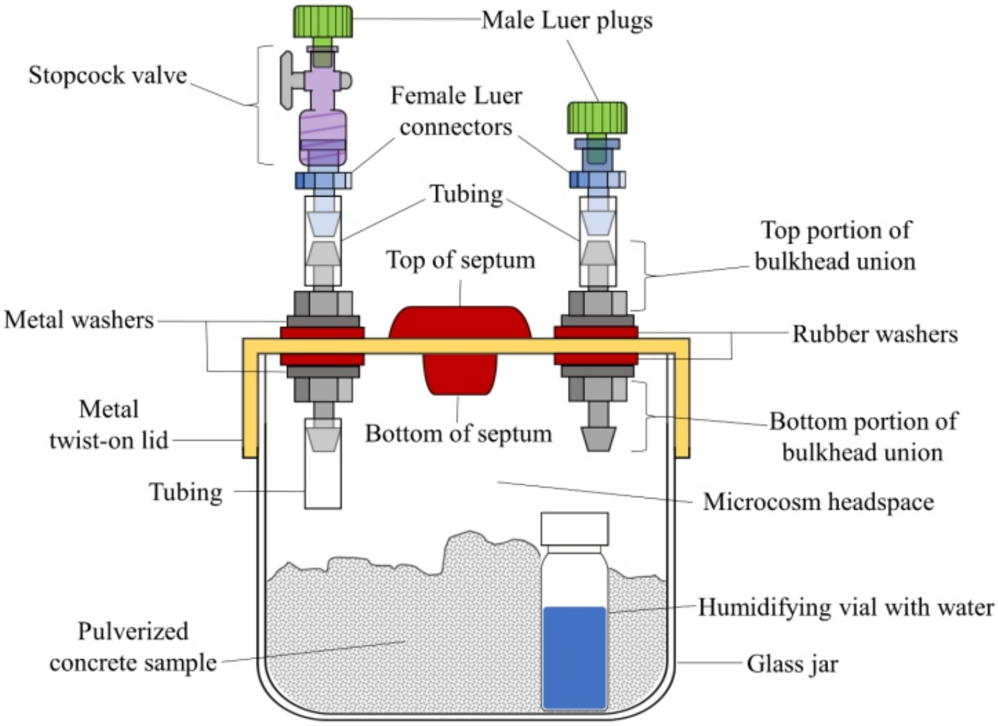

Figure 3. Schematic side-view/cross-section of a partially sealed microcosm.

In a laminar flow hood and using sterile technique, we transferred each concrete sub-sample to a microcosm along with a humidifying vial (8-mL, pre-sterilized, glass scintillation vial containing 4 mL of sterile, degassed water and a perforated screw-on cap; Figure 3). Each vial released water vapor via diffusion through the perforation in the vial cap, thereby humidifying the microcosm headspace without wetting the concrete. We temporarily sealed the microcosms immediately after sample loading and vial placement by screwing on the lid, pressing the plumbing putty around the bases of the inlets, outlets, and septa, covering the putty with plastic wrap, then wrapping laboratory film around the junction between the jar and lid and around the upper portions of the inlet and outlet.Immediately after this, we filled the microcosms with CO2-free air (Airgas® Ultra Zero Grade Air) to make any later CO2 increases more apparent (but see Section 4.4). We connected the pressurized cylinder of CO2-free air to the inlet of a microcosm via sterilized silicone tubing fitted with a 0.22-µm membrane filter (to limit airborne contamination of the microcosm). Once the inlet and outlet were open and unplugged, we flushed the microcosm with CO2-free air for 90 seconds at a rate of one liter per minute (LPM). Then, we plugged the outlet, immediately closed the stopcock valve on the inlet, detached the line connected to the inlet, and plugged the inlet. This prevented the backflow of atmospheric air into the microcosms, though it sometimes left the microcosms slightly pressurized. We depressurized the microcosms by inserting a sterile syringe into the septum of every flushed microcosm and allowing the syringe to backfill with microcosm air until a pressure equilibrium was reached between the syringe and microcosm. Thus, the excess microcosm air was trapped in the syringe and removed from the microcosm. We wrapped the ends of the inlets and outlets with laboratory film to finalize the sealing. We dark incubated the microcosms for 90 days at 23 °C.

After incubation, we analyzed the headspace gas of each microcosm for CO2 enrichment. First, we gently shook the microcosm to disperse the air trapped among the concrete fragments. Then, we inserted the needle of a gas-tight syringe into a microcosm's septum and further homogenized the headspace air by filling and emptying the syringe twice before finally withdrawing 10 mL of headspace air. Then, we injected this microcosm air sample into the injection chamber of our gas analysis system (Figure 4). We installed the injection chamber (an air-tight chamber built similarly to the sample microcosms but with a smaller, 57-mL jar) between the same CO2-free air source used to fill the microcosms and an infrared gas analyzer (FMS-1601-14, Sable Systems International). The CO2-free air continuously flowed through the injection chamber and gas analyzer so that baselines of 0.0012% CO2 (± 0.0005%) and 20.8% O2 (± 0.0005%) read consistently on the data logging software (ExpeData, v.1.9.13, Sable Systems International). We maintained these baselines with an incoming air flow rate of 1 LPM, an internal analyzer flow read between 195–199 ml per minute, an internal pump rate at 11.4%, and an ambient temperature at 23 °C. Preliminary testing showed that we did not need additional scrubbing columns and filters to maintain consistent analytical baselines.

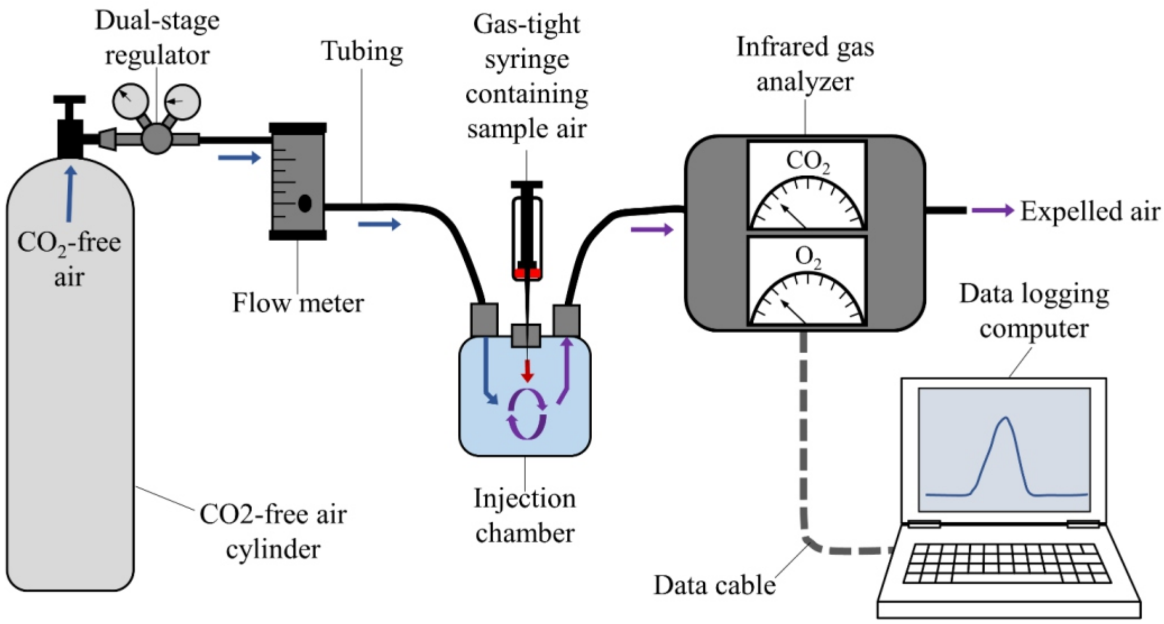

Figure 4. Schematic diagram of the gas analysis system in which CO2-free air carries air from experimental microcosms to a gas analyzer. Blue arrows indicate the direction of CO2-free air flow, red arrows represent sample air withdrawn from an incubated microcosm then injected into the analysis system, and purple arrows indicate the flow of CO2-free air combined with sample air.

After inserting the syringe needle into the injection chamber, we stabilized all components of the analysis system and initiated data logging for the sample. Then, we waited 15 seconds before quickly but steadily injecting the sample air. We waited 60 seconds after injection before removing the syringe and ending the logging cycle. Any injections containing CO2-enriched air registered as brief peaks on the otherwise flat CO2 baseline, while injections of non-enriched air registered without any peaks.

The microcosms that were filled with sterilized concrete and paired with microcosms filled with fresh concrete were the primary control microcosms. Additionally, we included a negative control group consisting of five microcosms loaded with 120 g of sterilized glass beads. The beads imitated the approximate mass and volume of the concrete samples in their microcosms while presumably eliminating the possibility of microbial activity. Any respiration signals from these microcosms would indicate gas leaks or other systemic problems. For positive controls, we incubated five microcosms loaded with of 120 g of soil (a silty-loam agricultural topsoil sample that we sieved and air-dried for approximately 30 days). We presumed this soil to be of low biomass but with enough microbial activity to easily register on our analysis system.

We noted CO2 enrichment when the air sampled from a microcosm produced a visible peak in the logged CO2 concentration data. Therefore, the area under the graphed peak was proportional to the level of CO2 enrichment that occurred in the corresponding microcosm. We calculated the area under the discernible peaks using the area integration function in the Expedata logging software. We integrated by seconds (the frequency at which the gas analyzer logged CO2 concentrations) and set the baseline at 0.0012 (the approximate mean CO2 concentration of the CO2-free carrier gas). Then, westandardized the peak areas for all concrete sub-samples by dividing each peak area value by the mass of concrete in its corresponding microcosm and multiplying that by 4.05 (to represent the 90-day incubation period as one year's worth of CO2 enrichment). We calculated relative and dimensionless measures of microbial respiration, which we refer to as "respiration values" because we could not confidently convert the peak areas to absolute molar units of CO2 efflux from the sample (e.g., µmol CO2 g-1 concrete s-1); we were unable to account for all the variables that affect peak development in the logged data (microcosm volume, sample injection volume, internal gas analyzer settings, etc.). However, these respiration values were suitable to determine if concrete endolith activity occurred and the relative levels of respiration among the samples (see Section 4.4 for further discussion).

For the concrete microcosms, we calculated the mean respiration value of duplicate microcosms (which had sub-samples from same bulk sample and were treated the same way in terms of sterilization). Then, we calculated the net respiration value of a concrete sample by subtracting the mean respiration value of its sterilized concrete microcosms from the mean respiration value of its associated fresh concrete microcosms (so that the net respiration value reflects only CO2 enrichment caused by live microbes in the sample).

3. Results

3.1. Possible quantities of endolithic biomass in concrete

We produced ten preliminary estimates of how much organic carbon is contained in the microbes living inside the global stock of concrete (Table 3). The estimates ranged from 4,579–1.14 million metric tons of Cmic. The final estimates were greatly influenced by differences between the mean and median DNA concentration and among the various conversion factors. Estimates based on our mean concentration of endolithic DNA were much higher than estimates based on the median concentration, even though these averages only differed by 0.027 µg g-1 concrete. The highest conversion factor (from Fornasier et al. [41]) produced estimates that were 14 times higher than estimates produced using the lowest conversion factor (Semenov et al. [39]).

Table 3. Estimates of endolithic Cmic contained in the global stock of concrete. We based these measurements on average microbial DNA concentrations from 25 concrete samples. We converted DNA concentrations to Cmic using one of five conversion factors and assumed the current global stock of concrete is 635.1 Gt.

DNA concentration average statistic	Conversion Factor Source	Conversion Factor	C_{mic} (µg g^{-1} concrete)	Global quantity of C_{mic} in concrete (metric tons)
Mean	Semenov et al. [39]	4.41	0.124829	79278.8
Mean	Anderson and Martens [40]	5.00	0.141529	89885.2
Mean	Fornasier et al. (*low*) [41]	12.00	0.339670	215724.5
Mean	Gong et al. [42]	38.11	1.078736	685105.1
Mean	Fornasier et al. (*high*) [42]	63.50	1.797421	1141542.3
Median	Semenov et al. [39]	4.41	0.007210	4579.3
Median	Anderson and Martens [40]	5.00	0.008175	5191.9
Median	Fornasier et al. (*low*) [41]	12.00	0.019620	12460.7
Median	Gong et al. [42]	38.11	0.062310	39573.0
Median	Fornasier et al. (*high*) [41]	63.50	0.103823	65937.7

For this study, we assumed that every microgram of Cmic represented 2.174 micrograms of total microbial biomass (which includes carbon and other elements). As such, our total biomass estimates were larger than our Cmic estimates but followed the same patterns of variation (Table 4). The global estimates ranged from 9955–2.48 million tons. Additionally, these estimations indicate that the "average" gram of concrete contains between 0.01–4 µg of endolithic biomass, depending on the assumptions of the calculations.

Table 4. Estimates of total endolithic biomass contained in the global stock of concrete. We based these measurements on average microbial DNA concentrations from 25 concrete samples. We converted DNA concentrations to Cmic using one of five conversion factors and assumed the global stock of concrete is 635.1 Gt. We converted Cmic to total microbial biomass by multiplying by 0.46.

DNA concentration average statistic	Conversion Factor Source	Conversion Factor	Total endolithic biomass (µg g^{-1} concrete)	Global quantity of endolithic biomass in concrete (metric tons)
Mean	Semenov et al. [39]	4.41	0.271367	172345.1
Mean	Anderson and Martens [40]	5.00	0.307672	195402.7
Mean	Fornasier et al. (*low*) [41]	12.00	0.738413	468966.4
Mean	Gong et al. [42]	38.11	2.345078	1489359.0
Mean	Fornasier et al. (*high*) [42]	63.50	3.907438	2481613.7
Median	Semenov et al. [39]	4.41	0.015675	9955.0
Median	Anderson and Martens [40]	5.00	0.017772	11286.8
Median	Fornasier et al. (*low*) [41]	12.00	0.042652	27088.4
Median	Gong et al. [42]	38.11	0.135456	86028.2
Median	Fornasier et al. (*high*) [41]	63.50	0.225701	143342.8

3.2. Respiration readings from endo-concrete samples

After 90 days, seven out of the ten concrete samples did not emit measurable amounts of CO_2 via microbial endolith respiration; however, two samples showed convincing (albeit low) respiration signals (Table 5). The air in duplicate microcosms containing one of the cinder block samples (RCMU-1) became slightly enriched with CO_2 over time (i.e., produced small peaks in the gas analysis outputs); meanwhile, their associated control microcosms, which contained sterilized portions of the same concrete, did not. These fresh sub-samples of R-CMU-1 had a mean respiration value of 0.0079 g-1 concrete year-1, which is about 10% of the mean respiration value calculated for the low biomass soil samples (respiration value = 0.076 g-1 concrete year-1). The microcosms holding concrete from a belowground sample of (R-Blwgrnd-2) also became enriched with CO_2, though only to about half the level of the microcosms holding the cinder block sample (having a mean respiration value about 5% of the soil's mean value). Additionally, the associated control microcosms behaved as expected, showing no signs of CO_2 enrichment.

One microcosm that contained a fresh sub-sample of underwater concrete (R-Submrg-1) showed a faint respiration signal, similar to that of the belowground sample, but its own duplicate sample did not. Furthermore, one of the associated control samples also showed a very faint respiration signal, which we noted as a sign of either abiotic CO_2 enrichment or an analysis error. In any case, the net respiration value for this sample was above zero but very low (0.0005 g-1 concrete year-1). The negative and positive control microcosm behaved as expected. The five negative control microcosms containing sterilized glass showed no CO_2 enrichments, while all positive control microcosms containing low biomass soil became enriched with CO_2 (respiration values ranged from of 0.063 to 0.084 g-1 soil year-1).

Table 5. Relative measures of CO_2 enrichment by concrete samples. The ten bulk samples of concrete are sorted by the general type of concrete and the relative CO_2 enrichment values are shown for 40 microcosms (20 fresh sub-samples and 20 sterilized sub-samples). We duplicated each sub-sample treatment into sub-replicates which we averaged into mean enrichment values. The net mean enrichment for each bulk sample equals the sample's respiration value (the level the endolithic respiration per g concrete per year).

Bulk sample ID	Sub-replicate number	Enrichment by fresh sub-replicate	Mean enrichment by fresh sub-replicates	Enrichment by sterilized sub-replicate	Mean enrichment by sterilized sub-replicates	Mean net enrichment (respiration value)
R-Submrg-1	1	0.0031	0.0015	0.0021	0.0009	0.0007*
	2	0		0		
R-Submrg-2	1	0	0	0	0	0
	2	0		0		
R-Blwgrnd-1	1	0	0	0	0	0
	2	0		0		
R-Blwgrnd-2	1	0.0034	0.0035	0	0	0.0035
	2	0.00.35		0		
R-Ground-1	1	0	0	0	0	0

R-Ground-2	1	0	0	0	0	0
	2	0		0		
R-Abvgrnd-1	1	0	0	0	0	0
	2	0		0		
R-Abvgrnd-2	1	0	0	0	0	0
	2	0		0		
R-CMU-1	1	0.0086	0.0079	0	0	0.0079
	2	0.0072		0		
R-CMU-2	1	0	0	0	0	0
	2	0		0		

*The lack of enrichment for all the corresponding fresh sub-replicates and the presence of an enrichment signal in one of the sterilized sub-replicates suggests that this is an erroneous measurement

4. Discussion

4.1. Concrete microbes as an overlooked pool of organic carbon

Without knowledge of incidental concrete endoliths, it would be difficult to imagine the interior volumes of concrete harboring life of any kind; even with knowledge of concrete endoliths, it would be difficult to imagine these microbes as a significant portion of the concrete's mass. Previous studies (and the difficulties thereof) indicated that concrete typically contains very little biomass, similar to many other endolithic and subsurface ecosystems. For example, Maresca et al. [21] found that conventional DNA extractions did not yield measurable amounts of DNA from concrete, and the precursor study to this one found that many sensitive tests were often unable to detect life within concrete [31]. Still, any microbial biomass inside concrete represents a hidden, yet globally distributed pool of organic carbon. We formally estimated the size of this pool so that we could begin deciding if this pool was consequential to concrete's overall carbon profile.

We relied on microbial DNA to estimate the Cmic concentrations. Several assumptions and tradeoffs were embedded in these estimates (discussed in Section 4.2), but we accounted for some uncertainty by reporting several estimates, each utilizing a unique set of parameters. Among individual concrete samples, we calculated widely varying estimates of Cmic. Both the low and high estimates are interesting, but we thought it appropriate to derive global estimates from the "average" levels of sample biomass [45]. We extrapolated upon the mean Cmic concentration (28.3 µg g-1 concrete) and the median (1.6). Both statistics indicated that most of our samples had low DNA concentrations, though these summarized our samples in slightly different ways, and these slight differences resulted in noticeably different global estimations.

Our most conservative estimate of the Cmic contained in the world's supply of concrete came to about 4579 metric tons (Table 2). This means that endolithic Cmic represents 0.000000721% of the total mass of concrete. If manufacturing one kg of concrete emits between 60–200 g of CO2 [13], then it follows that manufacturing one kg of concrete releases between 0.016–0.054 kg of carbon (carbon is 27.27% of the molar mass of CO2). Scaling up, this means that producing the world's current stock of concrete (635.1 Gt) released between 10.4 and 34.6 Gt of carbon. If our lowest Cmic estimate was considered as a quantity of carbon that was sequestered in the cells of concrete endoliths, then the presence of concrete endoliths could only offset between 0.000044% and 0.000013% of the carbon emitted thus far by the concrete industry. Therefore, our lowest global estimate of global Cmic depicts concrete endoliths as a miniscule carbon pool or sink that is inconsequential for most practical purposes. This estimate aligns with the general idea that concrete is not greatly affected by biology, and it was produced with what may be the most appropriate DNA-to-biomass conversion factor (4.41). This factor was developed by Semenov et al. [39] specifically for alkaline and carbonaceous soils, which may be the substrate that most closely resembles concrete (of all substrates that have been studied for microbial biomass).

Our highest estimate of Cmic residing in the global stock of concrete was about 1.1 million tons (Table 3). This implies that about 0.000179% of our concrete's mass is attributable to the organic carbon content of the endolithic microbes. With the same assumptions as before, this means that the biomass of concrete endoliths offsets between 0.011% and 0.0033% of cumulative carbon emissions from concrete. This brings concrete endoliths much closer to being an important carbon pool and carbon sink (assuming the endoliths can fix and stabilize carbon). This microbial carbon sink would not rival the sink capacity of abiotic cement carbonation, which might have allowed solidified concrete to cumulatively re-absorb as much as 6.5 billion tons of CO2-carbon [17] (see Section 1.2). Still, the endolithic Cmic pool might be large enough to offset some of the smaller sources of concrete-related emissions, such as the emissions associated with concrete disposal [46,47]. Moreover, while our estimate of 1.1 million tons might be inappropriate because it was based on a DNA-to-biomass conversion factor developed for microbe-rich arable soils [41], this estimate may reflect the ultimate potential and eventual condition of concrete. In other words, concrete may become more microbe-rich over time as it weathers and as its lithology changes to become more hospitable to microbes(sensu [48,49]). As this happens, the biomass levels and substrate conditions inside concrete may become more similar to those of soils. This would have global consequences because the world continues to accumulate old and discarded concrete [50].

Additionally, we estimated the global quantities of Cmic inside concrete using intermediate DNA to-biomass conversion coefficients (Table 3). These coefficients and the global estimates they produced (which ranged from 5191–685105 metric tons) demonstrate that the true value of global Cmic inside concrete could fall anywhere in between the highest and lowest estimates we discussed above. Furthermore, the various conditions under which the five coefficients were developed could provide clues as to how microbial biomass levels can be influenced by substrate pH [39,41], texture [41], mineral content [39], and moisture [40,42].

We focused on microbial carbon because, in the era of anthropogenic climate change, it is concrete's carbon profile that demands the most attention. However, we also estimated the total biomass of the concrete endoliths (which includes other elements besides carbon). In the context of concrete, the total microbial biomass is also an interesting metric because it represents the biological material fraction of concrete (a substrate that is often viewed as a purely mineral and abiotic). Because we assumed that carbon is roughly half the weight of microbial biomass [40], our total biomass estimates were roughly twice that of our Cmic estimates, ranging from 9995 tons to 2.48 million tons (Table 4). The lower estimate suggests that the endolithic biomass is unlikely to affect the global accounting of concrete material inflows and outflows, even when all biological matter is considered. The higher estimate suggests that concrete endoliths are on track to become a significant ecological guild that only exists because of human activity. Studies have documented how some isolated ecosystems acquired new functional guilds upon the arrival of exotic species [51,52]; however, the concrete endolith guild would have a global distribution, possibly occurring almost anywhere concrete is installed.

4.2. The uncertainty surrounding carbon and biomass estimates

Every term in our Cmic estimation equation (Eq 1) is associated with a unique set of uncertainties; however, to promote more refined and more robust studies in the future, we discuss some of the major sources of uncertainty and possible improvements. First, our estimates were based on the average DNA concentrations of our concrete samples. Although we sampled a wide variety of concrete structures, more reliable averages could be calculated from a sample set that is larger and encompasses more of the incredible variety seen in concrete structures around the world [53] but still includes old and discarded concrete, as we did.

We removed the top 5 mm from our concrete sub-samples. These surface ("epilithic") portions of concrete are interesting because many organisms can live and grow on concrete [54,55], but these were outside our study's scope. Furthermore, we could not estimate global concrete surface area as we did global concrete mass. Still, samples somehow trimmed closer to the concrete's surface (e.g., at 1–2 mm below the surface) or otherwise include more of the available endolithic material would provide a more complete picture of the endo-concrete environment. Additionally, we had no basis for weighting our DNA concentration averages according to the relative abundances of the various types of concrete (i.e., we found no information about how much concrete is cast in place versus pre-cast, nor how much concrete is positioned underwater, underground, at ground-level, or aboveground). However, if this information becomes available or if another way of meaningfully classifying concrete structures is developed, then more sophisticated weighted averages could be used.

We extracted DNA from concrete using a protocol that prioritizes the isolation of amplifiable, PCR-quality DNA instead of DNA quantification [38]. Future studies focused on biomassing should consider omitting late-stage purification steps because these may unnecessarily reduce extraction yields and lead to critical underestimates of biomass [41]. Future studies should also standardize the volume of DNA extracts, as done here, to make the DNA concentrations readings comparable among various samples (e.g., [56]). We vacuum centrifuged all our final extracts down to 50 μL, though other methods, such as more tightly controlled elutions, may be better for standardizing extract volumes.We converted the average DNA concentrations to Cmic concentrations using established conversion factors after attempts to measure biomass more directly with chloroform fumigationextractions (CFE) [57] were unsuccessful. We found no discernible differences in extractable carbon between fumigated and non-fumigated concrete samples, as well improbably high concentrations of carbon (data not shown). We anticipated this because concrete has several features that sometimes inhibit chloroform-based assays, including unconventionally low biomass levels [58], high proportions of dormant microbes [59], high substrate particle densities [60], and high substrate alkalinity and carbonate content [39]. Therefore, while we encourage future studies to explore other more direct biomassing methods for concrete samples, we utilized soil-based DNA-to-biomass conversion factors knowing that DNA data were obtainable (and useful for other experiments). The soil-based conversion coefficients varied widely, and we were unsure which coefficient was most appropriate for concrete, so we mitigated these problems by reporting several biomass estimates derived using several conversion factors.

Lastly, we assumed that 635.1 Gt of concrete is scattered across Earth. We figured this straightforwardly using a recent global estimate of concrete mass, a recent rate of global cement production, and an average cement-to-concrete ratio, but there is uncertainty associated with each of these parameters. The 2020 estimate of global concrete mass was compiled by Elhacham et al. [3]using information from prior studies concerning global socioeconomic material stocks [61], industrial metabolism [62,63], and mineral resource usage [7]. Yet, there are no complete national statistics of concrete production, primarily because of the sheer scale and decentralized manner of production and because concrete is a composite material assembled in various ways [7,13]. Thus, concrete amounts are estimated based on cement, a commodity whose production is tracked more closely (e.g., by the US Geological Survey and the Global Cement and Concrete Association). Yet, tracking cement production is not equivalent to tracking cement use. We can only assume that most cement ends up in concrete, though cement is also used to make mortar, stucco, and grouts. Additionally, we assumed that cement comprises between 10–15% of concrete's final mass based on the world's most common concrete mixture formulas [4,13,44], though there are numerous concrete mix types [7]. Another matter is concrete recycling, which involves breaking down concrete for use in new concrete mixtures [64]. Concrete recycling is feasible [65] and very common in some regions [66], but it is unclear how slows global concrete accumulation.

4.3. Endolithic respiration can sometimes cause concrete to release carbon

It would be one matter if microbes simply comprised a static, carbon-based component of concrete; however, it would be another matter if these microbes actively cycled carbon in or out of solid concrete. Therefore, we examined the release/efflux/outputting of CO2 from solidified concrete by respiring concrete endoliths. Respiration is key to understanding the functioning and activity of individual microbes, microbial communities, and the ecosystems that microbes inhabit [67,68]. Prior to this study, very few studies have mentioned the in-situ activity of concrete endoliths; Coombes et al. [33] described euendoliths boring into concrete substrates and Kiledal et al. [32] suggested that certain populations of concrete endoliths shrink and swell over time. However, we were specifically interested in the community-level metabolic activity because it relates to endolithic carbon cycling [69,70]. When we tested the hypothesis that small amounts of CO2 are released from concrete by respiring microbes, we found that most of the concrete endolith communities sampled did not cause concrete structures to release significant amounts of CO2, but there were notable exceptions.

The mean respiration value for our concrete samples was exceedingly low (0.0012) because seven out of ten samples had respiration values of zero. Zero values do not necessarily mean that the microbial communities within these samples were entirely inactive, but it does suggest that these communities were not active enough to cause their concrete ecosystems to be net sources of CO2. This fits the assumption that endolithic ecosystems within concrete generally function at slow rates and at low levels, like other endolithic ecosystems [28,71]. Even if the endoliths within concrete were metabolically active, it is possible (given our own biomass estimates) that there were too few concrete endoliths microbes to produce measurable respiration signals. Yet, two concrete samples, from a belowground structure and a pre-cast CMU, produced respiration signatures that we could attribute to microbial activity (as opposed to analytical error or abiotic processes; Table 5). We did not explicitly design our respiration tests to identify the factors that affect "concrete respiration," but the respiration signals from these two concrete samples suggests that a combination of three interrelated factors allowed these samples to develop microbial communities capable of respiring at significant levels. First, being positioned outdoors likely allowed these samples to receive more life-sustaining moisture and nutrients from rainwater, soil particles, etc., as well as additional microbes [21]. Second, these samples appeared very weathered and porous, and the presence of many large and interconnected pore spaces is known to promote processes such as nutrient diffusion and light penetration, which would in turn promote microbial colonization and overall metabolism [72]. Third, these samples came from structures that appeared several decades old. Thus, the concrete had probably carbonated and became less alkaline by the time of sampling; this change towards a more neutral pH could have allowed more microbes to survive inside these concrete structures [31].

Additionally, while the amount of carbon that respired from these sample was small (between one-tenth and one-twentieth of the carbon released by our low-biomass soil sample), these samples demonstrate the microbial carbon emissions from within concrete do occur in some instances. Future studies should attempt to quantify this phenomenon similar to how we attempted to quantify global concrete endolith biomass. We should also keep in mind that, as much of the world's concrete weathers and ages, that concrete may eventually come to harbor endolithic communities that are active enough to generate net outflows of carbon.

4.4. Some experimental concerns surrounding endolithic respiration tests

Several aspects of our respiration tests were experimental compromises between maximizing the detection of respiration signatures and minimizing sample manipulation and contamination. We opted to measure respiration ex situ in long-incubated microcosms because we presumed that the respiration rates would be too low to measure in the field in real time. Moreover, we loaded our microcosms with relatively large concrete samples (>70 g); we suspected that samples <50 g may not contain enough endolithic cells to produce detectable respiration signals. We half-filled the microcosms with concrete to reduce the headspace volume and increase the chances that the headspace air would become measurably enriched with CO2 [73]. Yet, given the preponderance of negative results here, we would now recommend filling the microcosms more.

To further maximize the chances of detecting CO2 enrichment, we initially filled our microcosms with CO2-free air. There are some analytical advantages associated with using CO2-free air during respiration experiments [74]. We avoided over-enrichment of CO2, which sometimes constrains microbial metabolism (in a type of negative feedback) and confounds respiration analyses [75]. Yet, it is possible that the lack of CO2 in the microcosms inhibited the functioning of any microbes that rely on CO2 assimilation (and the microbes that rely on these microbes). This could have reduced respiration levels below what would have otherwise been detectable. Repeating this experiment with microcosms filled with air containing CO2 may produce different results.

During the respiration assays, we used pulverized concrete samples instead non-pulverized samples because we decided that the benefits of such sample manipulation outweighed the costs. We suspected that intense grinding or powderization would signficantly alter the microbial communities. Yet, because of concrete's high density and particle arrangement, we also suspected that leaving the concrete samples intact would slow the diffusion of respired CO2 from the inside of the concrete to the surrounding headspace air (just as CO2 respired in soil is slower to diffuse when the soil is compacted; [76,77]). Therefore, to facilitate the detection of respired CO2, we pulverized the concrete but stopped short of intense grinding. Yet, even this may have caused the concrete to excessively dry out. The insides of concrete can contain water leftover from the initial mixing process and/or water that has seeped in from the external environment [78]. The microscopic sources of water usually amount to very little water, which is why our samples appeared dry, but this moisture can affect the functioning of concrete structures [79]. To counteract any moisture loss without adding too much excess water to the concrete, we included humidifying vials in each microcosm. Additionally, wedecided to not induce respiration by adding nutrients. Adding nutrient solutions to a substrate can activate or stimulate otherwise dormant and slow-growing microbes, thus causing their respiration to reach measurable levels. In this way, nutrient amendment is an effective life-detection strategy (e.g., [80,81]); however, our goal was not life detection – our goal was to determine if typical endolithic activity causes carbon emissions from concrete.

Concrete respiration analyses may also be confounded by carbonation. It is conceivable that some of the CO2 respired by concrete endoliths was reabsorbed by the cement in our concrete samples, thus preventing CO2 enrichment in the microcosm headspaces. A similar process can happen in soil when the CO2 respired by soil organisms is absorbed by soil chemicals before it can flow out of the soil [82]. Yet, this would not be an issue when the cement within the concrete is already fully carbonated and unable to absorb more CO2 (as is usually the case for old, damaged, or pervious concrete; [83]). Also, the CO2 respired by some concrete endoliths may have been assimilated by other concrete endoliths, which sometimes happens among soil microbes [84,85]. We have no evidence that CO2 assimilating microbes occur in the dark environments within concrete, but biological CO2 absorption within ordinary concrete deserves further investigation. Regardless of the many processes that produce or capture CO2 within concrete, our tests determined whether our concrete samples were net emitters of carbon, which is arguably the more important point in the context of global greenhouse gas emissions.

Finally, while we successfully tested our concrete respiration hypothesis, our tests did not produce absolute measures of carbon efflux (see Section 2.5). Therefore, we could not estimate the mass of carbon being emitted globally from concrete endoliths. Future studies should explore gas analyses that can measure concrete respiration in molar units, such as gas chromatography, or use gas standards to help convert respiration signals into molar masses.

5. Conclusions

In summary, we investigated endoliths as a global pool of organic carbon within concrete (Objective 1) and as agents of carbon flux from concrete (Objective 2), thus finding another connection between concrete microbiology and sustainability. Regarding the first objective, we demonstrated that trace levels of microbial biomass within concrete (>4 µg g-1 concrete) could add up to sizable global quantities of carbon (4500–1150000 metric tons). Our lower estimates implied that the amount of carbon locked up within concrete endolith biomass was too small to significantly alter carbon budget of concrete or the concrete industry, while the higher estimates implied that the Cmic of concrete endoliths may be enough to offset smaller sources of concrete-related carbon emissions.

Regarding our second objective, we tested the idea that carbon can be mobilized and emitted by the metabolic activities of concrete endoliths. We found that most of our concrete samples did not emit CO2 because of respiring endolithic microbes, which suggests that concrete endolith communities often comprise relatively few microbes and/or largely inactive microbes. Yet, we observed small but clear respiration signals from two concrete samples, suggesting that "concrete respiration" occurs under certain circumstances.

Our results are preliminary, but this study can serve as a template for future investigations. Moving forward, we suggest that concrete studies maintain some focus on microbial carbon storage and cycling because the carbon footprint of the concrete industry is expected to remain high in the coming decades [86], and Earth will continue accumulating concrete materials [87]. The current study was conducted in a piecemeal fashion, but an obvious improvement would be to measure biomass, respiration, and other carbon-related measurements in the same set of samples, as well as to correlate those biological measurements to other variables like concrete pH, density, and carbonation levels.This would allow researchers to identify which factors affect concrete endolith biomass and respiration rates. Additionally, future studies should use larger sample sizes, concrete from other regions, and more types of concrete, including new types of concrete that have been explicitly developed to have smaller carbon footprints [88,89]. Future studies should refine and explore other methods of measuring concrete endolith biomass and respiration. Global rates of concrete respiration may even be estimated once this process is further verified and quantified. Individual concrete samples should also be analyzed more closely to determine if microbes and microbial activity are concentrated in certain portions of concrete structures (e.g., near the surface, within carbonated zones, or within pore spaces). Additionally, there is a need to elucidate and quantify other ways carbon can be stored or released by microbes (e.g., the carbon contained in non-living organic matter, the carbon fluxes associated with microbial mineral precipitation and dissolution; [35,90]), as well as examine the fate of concrete as it decomposes in the environment and how this corresponds to microbial activity

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflict of interest.

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