Fuzzy-set Qualitative Comparative Analysis in Urban Agglomerations: A Survey on Low-Carbon Transition and Urban Sustainability

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Abstract

This survey paper explores the application of fuzzy-set Qualitative Comparative Analysis (fsQCA) in understanding low-carbon transitions within urban agglomerations. Urban agglomerations are pivotal in sustainability due to their significant contributions to greenhouse gas emissions and resource consumption. The paper underscores the importance of fsQCA as a methodological tool for analyzing the complex interdependencies and configurations that drive sustainable urban transformations. Through a comprehensive exploration of urban agglomerations' roles in low-carbon economies, the survey identifies driving pathways for sustainability transitions, emphasizing the integration of Information and Communication Technology (ICT) and urban planning. It also highlights the challenges and opportunities these agglomerations face, particularly in the global south, where unique socio-economic and infrastructural contexts demand tailored strategies. The survey further presents empirical evidence from carbon emission studies and case analyses, illustrating the utility of fsQCA in real-world scenarios. By advocating for methodological plurality, the paper suggests future research directions that focus on systemic changes, cultural dynamics, and the integration of social values in technological applications. Overall, the survey provides a nuanced understanding of fsQCA's role in advancing urban sustainability, offering insights into effective strategies for low-carbon transitions and the promotion of sustainable urban futures.

1 Introduction

1.1 Significance of Studying Urban Agglomerations

Urban agglomerations are crucial for sustainability and low-carbon transitions due to their significant economic, social, and environmental impacts. These densely populated regions contribute substantially to greenhouse gas emissions and resource consumption, making them central to global sustainability efforts [1]. The rapid urbanization and concentration of resources, populations, and economic activities in these areas present both opportunities and challenges for sustainable development [2]. As urban land expansion accelerates worldwide, the role of urban agglomerations in shaping sustainable futures becomes increasingly recognized [3].

The hospitality and tourism sectors face mounting pressure to implement environmentally sustainable practices within urban agglomerations, underscoring the critical nature of these areas in facilitating low-carbon transitions [4]. Additionally, urban agglomerations in the Global South encounter unique challenges and opportunities in adopting low-carbon strategies, highlighting the need for renewed research focus on these regions [5]. The limitations of traditional urban sustainability assessment methods further emphasize the necessity of developing efficient strategies for low-carbon transitions [6].

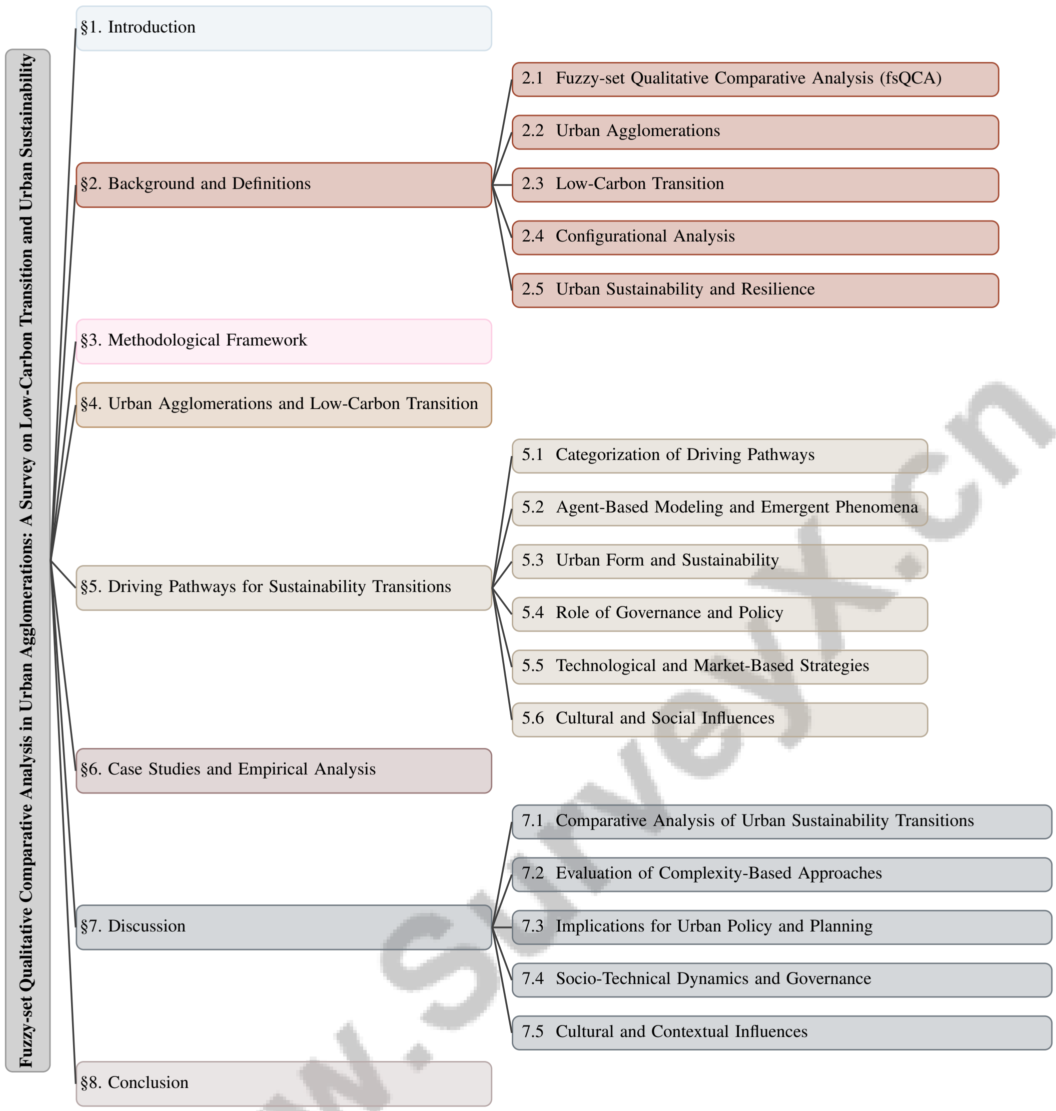

Figure 1: chapter structure

Urban agglomerations significantly influence carbon emissions and sustainability outcomes [7]. Despite their distinct historical contexts, urban economies exhibit universal patterns that underscore their importance in sustainability and low-carbon transitions [8]. Furthermore, startups and high-potential technology-based ventures play a vital role in driving economic development, innovation, and job creation, thereby contributing to the sustainability agenda [9]. Understanding the potentials and barriers to low-carbon development transitions in urban agglomerations is essential, particularly in regions where urban centers are integral to national sustainability strategies.

1.2 Role of fsQCA in Low-Carbon Transitions

Fuzzy-set Qualitative Comparative Analysis (fsQCA) offers a robust methodological framework for analyzing the complex interdependencies and configurations that drive sustainable urban transformations. It is particularly effective in identifying the intricate relationships among technological innovations, energy systems, and urban policies that facilitate low-carbon pathways [10]. By enabling researchers to explore how various innovations can be contextually combined and reconfigured, fsQCA aligns with the need to understand and implement sustainability transitions effectively [11].

Moreover, fsQCA integrates diverse analytical frameworks, such as its combination with Integrated Green Supply Chain Analysis (IGSCA), to assess the configurations leading to sustainable practices

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in sectors like hospitality and tourism [4]. This integration exemplifies fsQCA's capacity to analyze complex interactions influencing sustainability outcomes, thereby enhancing our understanding of effective low-carbon transition pathways [1].

fsQCA also addresses social implications in low-carbon transitions by providing insights into the equitable distribution of policy impacts, ensuring that socio-economic dimensions are adequately considered [12]. The transformative potential of Information and Communication Technology (ICT) in urban planning and development, as highlighted by fsQCA, underscores its role in facilitating low-carbon transitions through efficient resource management and innovative urban solutions [13].

1.3 Structure of the Survey

This survey aims to analyze the application of fuzzy-set Qualitative Comparative Analysis (fsQCA) as a methodological framework for understanding low-carbon transitions in urban agglomerations, elucidating causal pathways and equifinal outcomes in sustainability initiatives [14, 15, 16]. The introduction emphasizes the significance of urban agglomerations in sustainability and low-carbon transitions, followed by a discussion on the pivotal role of fsQCA in these processes and an outline of the survey's structure.

The second section, **Background and Definitions**, explores foundational concepts essential for understanding the survey's thematic focus, including detailed definitions of fsQCA, urban agglomerations, low-carbon transitions, configurational analysis, and urban sustainability and resilience.

In the **Methodological Framework**, the survey outlines the fsQCA methodology, detailing its relevance and application in urban studies, including discussions on its integration with other methodological approaches, specific applications, and case selection and calibration processes.

The fourth section, **Urban Agglomerations and Low-Carbon Transition**, examines the role of urban agglomerations in transitioning to low-carbon economies, addressing the challenges and opportunities they encounter, and discussing the integration of ICT and urban planning in facilitating these transitions.

The document titled systematically identifies and categorizes various pathways enabling sustainability transitions in urban agglomerations, emphasizing contextual reconfiguration and the interplay of multiple innovations in achieving sustainable urban infrastructures. This work aligns with broader research agendas in sustainability transitions, highlighting the need for empirical exploration and theoretical development to tackle the complexities of transitioning to sustainable urban futures [1, 11]. It illustrates how fsQCA identifies configurations leading to successful low-carbon transitions, discussing influences such as agent-based modeling, urban form, governance, policy, and socio-cultural factors.

The survey also includes a detailed examination of , demonstrating the practical application of fsQCA in various real-world contexts. It presents empirical evidence from carbon emission studies that highlight fsQCA's effectiveness in identifying intricate relationships between innovative business models and socio-technical dynamics. Additionally, the analysis reveals specific configurations of contextual antecedents influencing business model performance, such as adaptive agility and resource capability, providing valuable insights for practitioners and researchers [17, 2, 16, 15, 18].

In the **Discussion** section, the survey critically evaluates findings from the case studies, discussing their implications for urban policy and planning, and examining the roles of socio-technical dynamics and governance.

Finally, the **Conclusion** summarizes key insights, emphasizing fsQCA's contributions to understanding low-carbon transitions and suggesting future research directions. The survey advocates for methodological plurality in urban sustainability studies, promoting the integration of diverse research approaches to enhance understanding and assessment of sustainability in urban contexts. This recommendation stems from findings indicating that current urban sustainability assessments often lack a unifying framework and that mixed-methods research could better align assessments with established sustainability principles, leading to more effective strategies for sustainable urban development [5, 8, 11, 19].The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Fuzzy-set Qualitative Comparative Analysis (fsQCA)

Fuzzy-set Qualitative Comparative Analysis (fsQCA) is an effective methodological tool for exploring complex causal relationships, particularly within urban studies. By integrating qualitative and quantitative approaches, fsQCA identifies configurations of conditions leading to specific outcomes, thus addressing the complexity inherent in urban dynamics where multiple factors interact to influence sustainability and development [16, 2]. This method captures interactions among urban elements, such as socio-technical systems and governance structures, that traditional linear models often overlook [14]. fsQCA leverages underutilized data sources like Social Media Data (SMD) for real-time insights into urban behaviors [19], while advancements in data analytics, including Large Language Models (LLM), enhance the precision and efficiency of urban sustainability assessments [6]. Its versatility is evident in applications ranging from residents' support for tourism to the survival of green innovative enterprises, making it indispensable for crafting effective sustainable urban development strategies [20].

2.2 Urban Agglomerations

Urban agglomerations play a critical role in understanding urbanization and climate change dynamics. Defined through urban scaling theory, they are characterized by urban quantities that scale with city size, essential for analyzing growth and environmental impacts [21]. Accurate classification into Local Climate Zones (LCZs), based on morphological and climatic properties, is crucial for assessing these impacts [22]. As significant nodes of economic activity, urban agglomerations impact global energy consumption and CO2 emissions, with larger agglomerations potentially exhibiting greater efficiency in energy use and emissions compared to smaller cities, thus driving sustainability transitions [23]. However, challenges such as slum development and inadequate infrastructure, particularly in the global south, necessitate innovative, context-specific solutions [5]. Integrating Information and Communication Technology (ICT) into urban planning enhances resource management and governance, promoting sustainable development [13]. Methodologies like the City Clustering Algorithm (CCA) offer a more accurate representation of urban areas beyond traditional administrative boundaries [24]. Case studies of Chinese urban agglomerations, such as the Yangtze River Delta and Guangdong-Hong Kong-Macao, illustrate diverse challenges and opportunities in pursuing sustainability transitions [7].

2.3 Low-Carbon Transition

The low-carbon transition represents a pivotal transformation in socio-technical systems, crucial for addressing climate change and resource depletion [1]. It involves transitioning from carbon-intensive energy systems to sustainable alternatives to reduce greenhouse gas emissions. Urban agglomerations, as dense hubs of economic and social activity, are at the forefront of implementing innovative solutions to minimize carbon footprints, despite facing unique challenges, especially in the global south [5]. Framing the low-carbon transition within urban sustainability issues encompasses environmental, social, and economic implications, requiring a nuanced approach to achieve sustainable outcomes and address disparities in carbon emissions [7]. Understanding the dynamics of small and medium-sized green innovative enterprises is vital, particularly in regions like China, where their low life expectancy poses sustainability challenges [2]. Comprehensive policy-making and strategic planning are essential to align urban agglomerations with global climate goals, facilitating effective low-carbon transitions that integrate socio-economic considerations.

2.4 Configurational Analysis

Configurational analysis examines complex interrelationships among various conditions and their collective impact on specific outcomes, making it particularly relevant for urban sustainability studies [16]. By focusing on causal complexity, this approach uncovers multiple pathways leading to similar outcomes, providing a nuanced perspective on urban phenomena [15]. In urban sustainability, configurational analysis explores relationships between urban elements, including infrastructure and governance, within the spatial context of cities [25]. Integrating spatial models, such as the spatial STIRPAT model, enhances understanding by accounting for spatial effects and city interactions

[23]. This analysis supports the development of theoretical frameworks incorporating environmental factors to explain urban sustainability outcomes [26]. By capturing the complexity of urban systems, configurational analysis identifies conditions leading to successful sustainability transitions and examines entrepreneurial activities in urban settings, highlighting the role of perceived opportunities and capabilities in driving urban sustainability [14].

2.5 Urban Sustainability and Resilience

Urban sustainability and resilience are crucial in low-carbon transitions, reflecting the need for cities to adapt to climate change impacts while promoting sustainable development. The complexity of these concepts often leads to their vague and interchangeable use, hindering effective transformation processes [27]. A clear understanding of the distinct yet interconnected roles of sustainability and resilience is essential. Entropy plays a significant role in urban sustainability by quantifying disorder and diversity, informing urban planning and policy to enhance sustainability and resilience [28]. This aligns with the need for integrative frameworks incorporating core sustainability principles for comprehensive assessments [8]. Cultural dynamics significantly influence the success of low-carbon technologies, necessitating their incorporation into sustainability strategies to ensure social acceptance and effectiveness [29]. Entrepreneurs are pivotal in achieving the Sustainable Development Goals (SDGs), driving innovation within urban settings [18]. The potential of social media data (SMD) to enhance urban sustainability across various domains further emphasizes the importance of integrating diverse data sources [19]. Moreover, integrating emotional solidarity and economic benefits is crucial for shaping residents' attitudes towards sustainable practices, particularly in tourism contexts [20]. A multivariate approach is essential for evaluating urban sustainability and resilience, enabling a comprehensive understanding of interactions among urban elements [30]. By embracing these multifaceted perspectives, urban agglomerations can navigate the challenges and opportunities of low-carbon transitions, fostering environments that are both sustainable and resilient.

3 Methodological Framework

Category	Feature	Method
Introduction to fsQCA Methodology	Combinatorial Analysis	fsQCA[2], SRA[7], LLM-SA[6]
Integration with Other Methodological Approaches	Methodological Integration	CDAH[31]
Applications of fsQCA in Urban Studies	Configurational Analysis	ES[32]

Table 1: This table presents a comprehensive overview of the methodological approaches related to Fuzzy-set Qualitative Comparative Analysis (fsQCA), highlighting its core components, integration with other methodologies, and applications in urban studies. It categorizes the features and methods utilized in fsQCA, providing references to key studies that illustrate its implementation and significance in urban sustainability research.

The methodological framework in urban studies is pivotal for understanding the complex dynamics that underpin sustainability transitions. This section delves into methodologies that enable such analyses, with a particular emphasis on Fuzzy-set Qualitative Comparative Analysis (fsQCA). Renowned for its integration of qualitative and quantitative data, fsQCA offers a comprehensive lens through which to examine the intricate causal relationships inherent in urban environments. Table 1 provides an in-depth summary of the key methodological approaches and applications of Fuzzy-set Qualitative Comparative Analysis (fsQCA) within the context of urban studies, emphasizing its versatility and integration with other analytical frameworks. Additionally, Table 2 provides a comprehensive comparison of the Fuzzy-set Qualitative Comparative Analysis (fsQCA) methodology, illustrating its integration with other approaches and its diverse applications in urban studies. The subsequent subsection elucidates the core principles of fsQCA, underscoring its significance and applications in urban studies.

3.1 Introduction to fsQCA Methodology

Fuzzy-set Qualitative Comparative Analysis (fsQCA) is a sophisticated methodological tool that synthesizes qualitative and quantitative elements to explore complex causal relationships within urban systems. Its pertinence is especially evident in urban agglomerations, where it aids in analyzing

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multi-actor processes and the intricacies of urban transitions [1]. Key components of fsQCA include case selection, calibration, and truth table construction, all crucial for effective analysis [16].

As illustrated in Figure 2, the hierarchical structure of fsQCA methodology in urban studies is depicted, highlighting its key components, applications, and innovative data processing techniques. This visual representation underscores fsQCA's utility in urban studies, further amplified by its capacity to discern and evaluate combinations of internal and external resources that contribute to urban sustainability [2]. This capability is vital for understanding how different configurations of conditions lead to specific sustainability outcomes. Additionally, fsQCA benefits from innovative data processing, such as Large Language Models (LLMs), which enhance the precision of urban sustainability evaluations by aligning assessments with the ISO 37101 framework [6].

Empirical research highlights fsQCA's efficacy in analyzing combinatorial effects of antecedent conditions, as demonstrated in studies of green behaviors in tourism [20]. This versatility makes fsQCA a valuable tool for addressing diverse urban challenges. Moreover, its integration with other analytical methods, like Synergistic CO2 Reduction Analysis (SRA), which examines the synergistic effects of carbon emissions reduction through disparity and social network analysis, expands its potential in urban sustainability research [7].

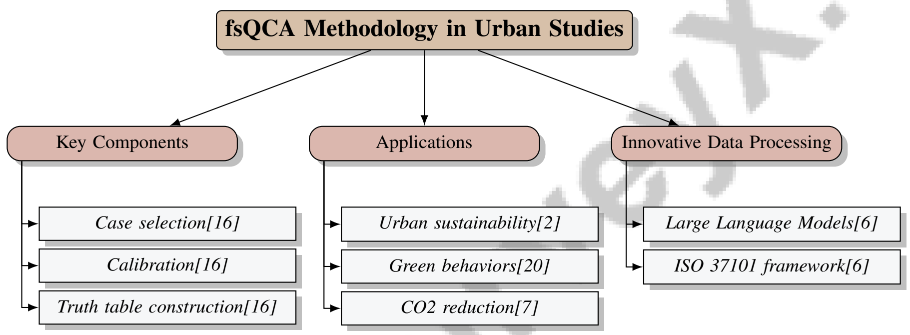

Figure 2: This figure illustrates the hierarchical structure of fsQCA methodology in urban studies, highlighting key components, applications, and innovative data processing techniques.

3.2 Integration with Other Methodological Approaches

Integrating fsQCA with other methodological approaches offers significant advantages for comprehensive urban sustainability research. The complexity of urban systems, characterized by non-linear dynamics and feedback loops, necessitates methodological pluralism to adequately capture socio-economic interactions and their sustainability implications [31]. By combining fsQCA with alternative analytical frameworks, researchers can bolster the robustness and depth of their analyses, thereby achieving a more realistic representation of urban phenomena.

One promising integration avenue involves combining fsQCA with experimental methods, which can complement traditional approaches and facilitate theory development in areas such as servitization [16]. This synergy enables the exploration of causal mechanisms and the validation of theoretical propositions, enriching the insights gained from fsQCA studies. Furthermore, integrating fsQCA with quantitative modeling techniques, such as agent-based modeling and system dynamics, can illuminate the complex interdependencies within urban systems, providing a holistic understanding of sustainability transitions.

The fusion of fsQCA with advanced data analytics tools, including LLMs and machine learning algorithms, significantly enhances its effectiveness in managing and interpreting extensive datasets. This integration allows for the extraction of nuanced insights, particularly in complex business environments where contextual factors influence outcomes, as demonstrated in studies on business model innovation and urban sustainability assessments [6, 15]. By leveraging these technological synergies, fsQCA can comprehensively assess urban sustainability initiatives, addressing multifaceted challenges and contributing to innovative low-carbon transition solutions.

3.3 Applications of fsQCA in Urban Studies

Fuzzy-set Qualitative Comparative Analysis (fsQCA) has become a pivotal tool in urban studies, facilitating a nuanced understanding of the intricate interplay of factors driving urban sustainability transitions. By employing fsQCA, researchers can systematically evaluate relationships between various antecedents and outcomes, yielding deeper insights into the configurational dynamics of urban environments [15].

A notable application of fsQCA is in analyzing urban form and its effects on sustainability outcomes. For example, configurational approaches applied in Nice utilize methodologies such as Space Syntax, Multiple Centrality Assessment, and Mark Point Parameter Analysis to investigate how urban form influences social and environmental dynamics [25]. These methodologies enable a detailed examination of spatial configurations and their implications for urban planning and policy development.

Furthermore, fsQCA has proven instrumental in modeling interactions among diverse market actors within urban energy systems. The ElecSim model effectively captures the complex dynamics of market behaviors and carbon tax strategies, providing valuable insights into their effects on emissions and costs [32]. This application underscores fsQCA's utility in evaluating policy interventions and their effectiveness in promoting low-carbon transitions.

Beyond urban form and energy systems, fsQCA has been employed to tackle a wide array of urban challenges, from green behavior in tourism to the survival of innovative enterprises. By identifying specific conditions contributing to successful sustainability outcomes, fsQCA offers a comprehensive framework for recognizing best practices and informing strategic decision-making in urban development. This approach integrates diverse economic and social factors while aligning with sustainability principles, enhancing the effectiveness of urban sustainability assessments and guiding policymakers in fostering opportunity-driven entrepreneurship in urban settings [8, 17, 18]. Through these varied applications, fsQCA continues to deepen our understanding of urban sustainability, providing a robust approach to addressing the multifaceted challenges of contemporary urban environments.

3.4 Case Selection and Calibration in fsQCA

The processes of case selection and calibration are essential in implementing fuzzy-set Qualitative Comparative Analysis (fsQCA), significantly influencing the reliability and validity of causal explanations derived from the analysis, thereby affecting the overall robustness of research findings [14, 17, 15, 16]. This process begins with the careful selection of cases relevant to the research question, ensuring a diverse range of conditions and outcomes is encompassed. Such diversity is vital for capturing the complexity of urban sustainability transitions and identifying various pathways leading to successful outcomes.

Calibration plays a crucial role in fsQCA, involving the assignment of precise membership scores to cases, which is essential for accurately identifying causal relationships and configurations influencing outcomes like organizational performance and innovation [17, 15, 16]. This step translates qualitative data into quantitative measures reflecting the degree to which each case exhibits the conditions of interest. It requires a nuanced understanding of the context and theoretical framework guiding the study, alongside methodological rigor to ensure consistency and accuracy in the calibration process. The calibration of conditions must be grounded in empirical evidence and theoretical insights, allowing for meaningful comparisons across cases.

The integration of Information and Communication Technology (ICT) in urban environments exemplifies how case selection and calibration can be applied in fsQCA studies. By analyzing case studies where ICT has been implemented, researchers can assess its impact on sustainability and highlight the methodological framework used for evaluation [13]. This approach facilitates the examination of diverse urban contexts and the identification of configurations that enhance sustainability outcomes.

However, challenges such as sample bias, data accuracy, and ethical considerations regarding the use of personal data without consent must be addressed to ensure the reliability of the analysis [19]. These issues underscore the importance of a rigorous methodological approach in case selection and calibration, ensuring findings are both valid and ethically sound. Through careful selection and calibration, fsQCA provides a powerful tool for uncovering the complex causal relationships driving urban sustainability transitions.

Feature	Introduction to fsQCA Methodology	Integration with Other Methodological Approaches	Applications of fsQCA in Urban Studies
Data Integration	Qualitative And Quantitative	Methodological Pluralism	Configurational Analysis
Application Scope	Urban Systems	Urban Sustainability	Urban Form, Energy
Analytical Techniques	Case Selection, Calibration	Experimental, Quantitative	Space Syntax, Elecsim

Table 2: This table presents a comparative analysis of the Fuzzy-set Qualitative Comparative Analysis (fsQCA) methodology, its integration with other methodological approaches, and its applications within urban studies. It highlights key features such as data integration, application scope, and analytical techniques across different contexts, underscoring the versatility and adaptability of fsQCA in urban research.

4 Urban Agglomerations and Low-Carbon Transition

4.1 Role of Urban Agglomerations in Low-Carbon Economies

Urban agglomerations play a pivotal role in advancing low-carbon economies by acting as centers of innovation and sustainable practices. These densely populated areas are instrumental in transforming infrastructure to support low-carbon pathways, significantly reducing carbon footprints [11]. As economic hubs, they adeptly manage existing fossil-fuel infrastructures while transitioning to sustainable energy systems, such as low-carbon electricity [32]. Models like STIRPAT demonstrate that larger urban agglomerations often achieve greater energy efficiency and lower per capita carbon emissions, highlighting their potential for substantial energy savings and emissions reductions [23]. These regions drive innovative practices and engage diverse stakeholders in sustainability initiatives, underscoring their critical role in low-carbon economies [1]. In the Global South, urban agglomerations often generate context-specific innovative solutions through grassroots initiatives, addressing challenges like slum development and inadequate infrastructure while promoting sustainable urban growth [5]. Methodologies such as the City Clustering Algorithm (CCA) provide insights into urban sprawl and the effectiveness of spatial planning in supporting low-carbon objectives, aiding in policy development necessary for low-carbon transitions [24]. Moreover, urban agglomerations foster green innovative enterprises, crucial for transitioning to low-carbon economies. These enterprises significantly contribute to economic development and the sustainability agenda, as seen in sectors like hospitality and tourism [4]. However, challenges such as differentiating urban forms and identifying central features within street networks necessitate tailored strategies to address each agglomeration's unique characteristics [25]. The anticipated increase in urban land by 1.8–5.9 times by 2100 in both developing and developed regions underscores the urgency of sustainable urban planning practices [3].

4.2 Challenges in Low-Carbon Transitions

Urban agglomerations face complex challenges in transitioning to low-carbon pathways, requiring comprehensive strategies for sustainable urban futures. A primary challenge lies in the overestimation of central government capacities and underestimation of societal dynamics influencing transitions, which can impede effective policy implementation [10]. Additionally, reliance on equilibrium and optimization-based models often overlooks the complexity of multi-agent interactions and agent heterogeneity, leading to indecisiveness in policy action and hindering progress towards low-carbon goals [31]. Cultural barriers also pose significant challenges to the acceptance and integration of low-carbon technologies, slowing sustainable practice adoption and transition processes [29]. The transition may result in job losses in fossil fuel sectors, increased energy prices for low-income households, and potential land and livelihood compromises due to the expansion of low-carbon technologies [12]. Managing these socio-economic impacts is essential for ensuring equitable transitions. The integration of diverse sustainability indicators further complicates the transition process, as urban agglomerations often lack a clear theoretical framework for these indicators, hindering coherent sustainability strategy development [8]. Traditional assessments of urban sustainability initiatives are time-consuming and require expert intervention, posing additional challenges for urban agglomerations in their low-carbon transition efforts [6].

4.3 Opportunities for Sustainability Transitions

Urban agglomerations provide numerous opportunities for facilitating sustainability transitions, leveraging their unique characteristics to drive transformative change. These areas serve as innovation hubs, offering fertile ground for the development and implementation of sustainable practices and technologies [18]. The concentration of resources and expertise within urban agglomerations fosters opportunity-driven entrepreneurship, essential for advancing sustainability goals. High country risk scores and GDP per capita, along with specific Sustainable Development Goals (SDGs), are necessary conditions for enhancing entrepreneurial activities that contribute to sustainability transitions [18]. The integration of multivariate modeling approaches enhances predictions regarding urban resilience and sustainability. By adopting comprehensive analytical frameworks, urban agglomerations can gain holistic insights into their systems, enabling effective planning and policy-making to support sustainable development [30]. This approach identifies key leverage points within urban systems, facilitating targeted interventions that promote sustainability outcomes. Social dynamics within urban agglomerations also present opportunities for fostering supportive environments for sustainability transitions. Residents' attitudes and subjective norms significantly influence their support for sustainable initiatives, as evidenced in tourism contexts [20]. Community engagement can overcome negative perceptions and encourage the adoption of sustainable practices, highlighting the importance of social cohesion in driving sustainability transitions. Urban agglomerations benefit from their capacity to integrate diverse sustainability indicators, providing a comprehensive framework for assessing and enhancing urban sustainability. Leveraging advanced data analytics and innovative methodologies, such as large language models for automating sustainability assessments, can streamline evaluations and enhance decision-making processes [6]. This integration of technology and data-driven insights holds significant potential for advancing urban sustainability and achieving low-carbon transitions.

4.4 Integration of ICT and Urban Planning

Integrating Information and Communication Technology (ICT) with urban planning is pivotal for facilitating low-carbon transitions within urban agglomerations. ICT provides innovative solutions to urban planning challenges, enhancing the efficiency and sustainability of urban systems. Its transformative potential lies in enabling real-time data collection and analysis, supporting informed decision-making and resource management optimization [13]. ICT facilitates the development of smart urban infrastructures that monitor and manage energy consumption, transportation systems, and waste management, contributing to carbon emissions reduction. By implementing smart grids and intelligent transportation systems, ICT enhances urban service efficiency and minimizes environmental impacts, aligning with low-carbon transition objectives. This alignment is crucial for assessing progress towards sustainability, necessitating comprehensive urban sustainability assessments to effectively measure and guide transitions [1, 8]. Moreover, ICT supports participatory urban planning processes by fostering collaboration among stakeholders, including government agencies, private sector actors, and local communities. This collaborative approach ensures initiatives are inclusive and tailored to address the unique needs of diverse urban populations, particularly in rapidly urbanizing areas. By integrating various perspectives, urban development strategies become more responsive to socio-economic disparities and environmental sustainability goals, fostering equitable and resilient urban environments [6, 5, 13, 8, 27]. Engaging citizens in the planning process enhances transparency and accountability while promoting sustainable urban development. The integration of ICT into urban planning also facilitates the adoption of innovative urban solutions, such as green building technologies and sustainable transportation systems. These solutions are crucial for developing resilient urban environments that adapt to climate change impacts and align with long-term sustainability objectives, particularly in the Global South, where unique challenges and opportunities for sustainable transformation are most pronounced [5, 27]. By incorporating ICT into urban planning, cities can effectively navigate the complexities of low-carbon transitions and achieve sustainable urban futures.

5 Driving Pathways for Sustainability Transitions

Understanding the pathways that facilitate sustainability transitions within urban agglomerations is crucial for addressing their complex nature. This section categorizes these pathways, examining strategies and configurations that contribute to low-carbon transitions, enhancing our understanding of the factors shaping sustainable urban development and informing targeted strategies for effective implementation. Figure 3 illustrates the hierarchical structure of driving pathways for sustainability transitions, highlighting key categories such as governance, technological strategies, and cultural influences. This figure further details their subcategories and impacts on sustainable urban development, thereby providing a visual representation that complements the discussion of these critical pathways.

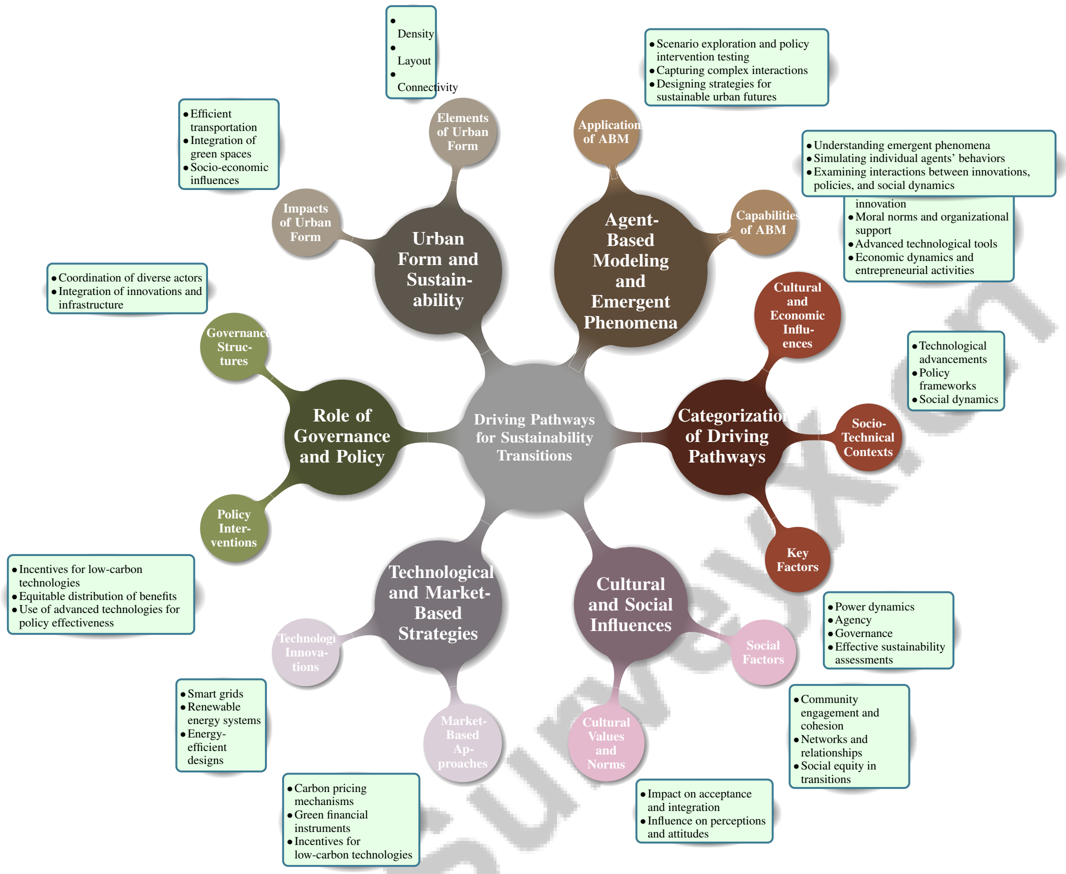

Figure 3: This figure illustrates the hierarchical structure of driving pathways for sustainability transitions, highlighting key categories such as governance, technological strategies, and cultural influences, and detailing their subcategories and impacts on sustainable urban development.

5.1 Categorization of Driving Pathways

Driving pathways for sustainability transitions are categorized by examining diverse strategies that enable low-carbon transformations. Key factors include power dynamics, agency, governance, and effective sustainability assessments [5, 11, 1, 8, 27]. Socio-technical contexts, where systemic interactions drive transitions, highlight the interplay between technological advancements, policy frameworks, and social dynamics [1]. In the Global South, urban governance and social inclusion are critical pathways for addressing regional challenges [5].

Cultural factors significantly impact transitions, requiring organizations to foster cultures that promote knowledge sharing and innovation [17]. Pathways influenced by moral norms, organizational support, and past green behavior emphasize internal dynamics in promoting sustainable practices [4]. Advanced technological tools, such as Large Language Models with the ISO 37101 framework, enable rapid assessments of urban sustainability initiatives [6], while Social Media Data enhances urban planning and decision-making [19].

Economic dynamics and entrepreneurial activities are also vital. A dual-method approach using Structural Equation Modeling and fsQCA illustrates configurations driving intentions and behaviors, such as in wine tourism [33]. Stable causal recipes for high Total Early-stage Entrepreneurial Activity countries underscore entrepreneurial attitudes' role in transitions [14]. The interconnectedness of urban agglomerations influences emissions, necessitating interventions tailored to each agglomeration's characteristics [7]. Variability in urban land projections across scenarios highlights societal choices' importance in shaping development trajectories [3].

5.2 Agent-Based Modeling and Emergent Phenomena

Agent-based modeling (ABM) offers a powerful approach for understanding emergent phenomena within sustainability transitions. It improves realism in modeling socio-economic interactions and captures complex dynamics challenging to analyze through traditional methods [31]. By simulating individual agents' behaviors, ABM explores how micro-level actions lead to macro-level outcomes, providing insights into technology adoption and policy effectiveness.

ABM is particularly useful for examining interactions between technological innovations, policy interventions, and social dynamics influencing urban development trajectories. It simulates diverse agents and adaptive behaviors, offering insights into paths urban agglomerations might follow in transitioning to low-carbon economies. This modeling captures complex interactions and self-reinforcing dynamics, accounting for historical and contextual factors influencing cities' evolution. ABM elucidates the interplay between innovations, socio-economic conditions, and policies, offering a nuanced understanding of pathways cities may adopt in achieving sustainable urban mobility and infrastructure reconfiguration [21, 11, 31]. It reveals conditions under which sustainability outcomes emerge, enhancing understanding of urban systems' interdependencies.

ABM facilitates scenario exploration and policy intervention testing, allowing policymakers to assess potential impacts before implementation. This capability is essential for developing effective policies driving sustainability transitions while minimizing unintended consequences. By capturing complex interactions among diverse agents, ABM provides a robust framework for analyzing dynamics driving sustainability transitions, aiding in designing strategies tailored to foster sustainable urban futures, particularly in the Global South [1, 11, 5].

5.3 Urban Form and Sustainability

The relationship between urban form and sustainability outcomes is critical, as spatial organization significantly influences environmental, social, and economic dynamics. Urban form elements such as density, layout, and connectivity shape sustainability trajectories. The concept of entropy provides insights into urban form, offering a lens for analyzing organization and efficiency [28].

Entropy in urban form refers to the degree of disorder within a system. High entropy levels may indicate inefficient organization, leading to increased energy consumption and degradation, while low entropy often supports sustainable resource use. Examining entropy informs planning and policy-making, enabling strategies enhancing sustainability by understanding urban systems' complex interactions [5, 8, 28, 30].

Compact and connected urban forms facilitate efficient transportation, reducing reliance on private vehicles and promoting public transit, cycling, and walking. This shift lowers emissions and enhances social equity by improving access to services. Urban forms integrating green spaces and fostering mixed-use developments enhance air quality, promote biodiversity, and improve quality of life, supporting ecological health and addressing disparities [5, 8, 11, 13].

Socio-economic factors like income distribution, housing affordability, and land use policies influence urban form and sustainability. Understanding interactions between urban form and socio-economic dimensions is crucial for fostering sustainable growth. Recognizing complex relationships among ecological, economic, and political factors and addressing inherent conflicts is vital. A collaborative approach engaging diverse stakeholders can develop holistic solutions leveraging sustainable development's synergistic effects on urban organization, leading to resilient environments [3, 13, 25].

5.4 Role of Governance and Policy

Governance and policy are essential for facilitating sustainability transitions within urban agglomerations, establishing frameworks guiding integration of innovations and infrastructure reconfigurations. Effective governance structures coordinate diverse actors, ensuring policies align with sustainability goals and respond to unique urban challenges [1, 11]. Integrating governance and policy fosters collaboration among government agencies, private sector stakeholders, and civil society, enabling co-creation of solutions for sustainable development.

Policy interventions shape transitions by providing incentives and frameworks encouraging low-carbon technologies and practices, including financial incentives, subsidies, and regulations mandating energy efficiency and emissions reductions. A comprehensive policy framework expedites transitions, fostering investments in sustainable infrastructure while addressing potential adverse impacts on vulnerable sectors [12, 10]. Effective policy shifts, as evidenced in China's low-carbon development, catalyze changes in energy systems, planning, and industrial practices, driving holistic transformation toward sustainability.

Governance and policy frameworks must address socio-economic dimensions, ensuring equitable distribution of benefits across urban populations. Implementing policies supporting inclusion, such as affordable housing and sustainable transportation, is crucial. Prioritizing equity within governance helps cities address transition challenges, reducing adverse effects on vulnerable populations. This approach promotes inclusivity and enhances resilience, ensuring transformative solutions are equitable and accessible, particularly as urban areas face climate change and rapid growth pressures [1, 27].

Integrating innovative data analytics and digital technologies enhances governance and policy effectiveness. Advanced technologies, including LLMs and machine learning, improve policy assessments' accuracy and facilitate real-time monitoring. LLMs automate and standardize assessments by categorizing projects, enhancing consistency and efficiency. Big data from social media provides insights into behavior and values, enriching decision-making and fostering comprehensive perspectives on socio-ecological interactions [1, 8, 6, 19]. These technologies offer insights into urban systems' performance, supporting evidence-based decision-making and policy improvement.

5.5 Technological and Market-Based Strategies

Technological and market-based strategies are pivotal for facilitating low-carbon transitions within urban agglomerations, offering solutions and incentives for sustainable development. Technology transforms infrastructures and processes, enabling cities to reduce carbon footprints and enhance resource efficiency. Technologies like smart grids, renewable energy systems, and energy-efficient designs play crucial roles in facilitating pathways, equipping cities with tools to meet goals. These innovations enhance energy management, reduce emissions, and address socio-economic and environmental challenges [8, 13].

Smart grids improve energy distribution by integrating renewable sources, enabling real-time monitoring, and allowing dynamic management. This integration supports low-carbon energy systems' development and enhances infrastructures' responsiveness to demands and conditions. Smart grids leverage IoT and big data analytics to optimize energy use and promote development [19, 29, 10, 1, 32]. This innovation supports transitions by reducing fossil fuel reliance and promoting clean alternatives. Additionally, energy-efficient building technologies contribute to significant consumption and emissions reductions.

Market-based strategies enhance technological advancements' effectiveness by establishing incentives and frameworks promoting low-carbon technologies while addressing eco-networks' complexities [29, 10, 15]. Carbon pricing mechanisms, like taxes and cap-and-trade, internalize emissions' costs, incentivizing reductions. These approaches align economic interests with objectives, fostering a competitive environment driving innovation and investment.

Green financial instruments, including bonds and sustainability-linked loans, channel investments into projects, facilitating transitions to sustainable practices. These tools mobilize capital and align with efforts to mitigate climate change, particularly in regions like China, where shifts toward technologies address challenges [29, 12, 10, 1, 8]. These products offer investment opportunities, facilitating fund flows toward initiatives supporting development. By leveraging markets, agglomerations can accelerate strategies' implementation and achieve targets.

5.6 Cultural and Social Influences

Cultural and social factors significantly influence sustainability transitions within urban agglomerations, affecting adoption and diffusion of practices and technologies. Integrating ICT innovations underscores cultural and social dimensions' importance in driving transitions [13]. ICT facilitates developing infrastructures promoting practices, yet effectiveness often depends on cultural context and social dynamics.

Cultural values and norms impact acceptance and integration, shaping perceptions and attitudes toward initiatives. Societies prioritizing values promoting stewardship are more inclined to adopt practices and facilitate technologies' integration, as evidenced by norms and behaviors influencing transitions and outcomes [1, 8, 13, 29]. Conversely, resistance can hinder adoption, necessitating strategies to overcome barriers and foster a culture of sustainability.

Social factors, including community engagement and cohesion, are equally important. Active participation enhances initiatives' effectiveness and ensures responsiveness to populations' needs. Networks and relationships play crucial roles in disseminating practices, as individuals are more inclined to adopt behaviors endorsed by peers. Research supports dynamics' influence on behavior change, highlighting engagement and support's importance in driving transitions. Integrating social media data into research underscores potential for insights into behaviors and values, enhancing understanding of networks facilitating practices' adoption [1, 19]. This influence is critical for scaling initiatives and achieving widespread adoption.

Social equity in transitions addresses potential impacts on vulnerable communities during shifts to low-carbon economies. Rapid transitions can lead to job losses, increased costs, and disruptions if not managed equitably. Incorporating equity considerations into strategies fosters inclusive and just transitions, ensuring all stakeholders are represented and supported [1, 12]. Ensuring equitable distribution of benefits is vital for fostering inclusive and resilient environments. Policies prioritizing equity and addressing marginalized communities' needs contribute to transitions' success, enhancing cohesion and supporting futures.

6 Case Studies and Empirical Analysis

6.1 Empirical Evidence from Carbon Emission Studies

Empirical research underscores the importance of configurational analysis in advancing urban sustainability and facilitating low-carbon transitions. The So2Sat LCZ42 benchmark illustrates how configurational analysis improves urban environment classification accuracy, essential for effective sustainability management [22]. This is exemplified by the analysis of population data from 61,224 points in the USA and a high-resolution grid of 5.75 million cells in Great Britain, offering insights into urban spatial dynamics beyond traditional Metropolitan Statistical Areas (MSAs) [24].

Further evidence is provided by the evaluation of 29 green innovative enterprises in China, which applies fsQCA to identify conditions favorable for urban sustainability, especially in green innovation contexts [2]. Historical carbon emission data from three urban agglomerations reveal the synergistic effects of urban dynamics on emissions, offering a nuanced understanding of factors driving low-carbon transitions [7].

The application of large language models (LLMs) in urban sustainability initiatives highlights the potential of advanced analytical methods in supporting low-carbon transitions. Studies utilizing datasets from the Paris Participatory Budget and the PROBONO Horizon 2020 project demonstrate the efficacy of LLM-based methods in providing actionable insights for policy development and implementation [6].

In the hospitality and tourism sectors, a survey of 277 employees illustrates the effectiveness of a hybrid methodological approach in assessing green behavior, emphasizing the integration of diverse analytical frameworks to capture sustainability transitions' complexities [4]. This aligns with research highlighting the importance of understanding urban land dynamics, providing a robust framework for modeling long-term urbanization trends critical for managing future urban growth [3].

These empirical studies underscore the effectiveness of diverse governance structures and analytical methods in facilitating successful low-carbon transitions. They highlight the necessity for comprehensive and integrative approaches to urban sustainability, enabling planners and policymakers to devise targeted strategies that address urban agglomerations' unique challenges and opportunities, thereby contributing to global sustainable development efforts [1].

6.2 Innovative Business Models and Sustainability

Innovative business models play a crucial role in promoting sustainability within urban agglomerations by fostering sustainable practices and technologies. These models harmonize environmental, social, and economic objectives, generating value for businesses while advancing comprehensive sustainability goals. Methodologies such as the application of large language models (LLMs) streamline the evaluation of initiatives against established sustainability frameworks, enhancing assessment effectiveness and consistency, and providing a holistic perspective on project impacts [1, 6]. A key aspect is their focus on circular economy principles, emphasizing resource efficiency, waste reduction, and continuous material use through recycling and reuse.

Adopting circular economy practices mitigates environmental impact and enhances economic resilience by reducing reliance on finite resources. This aligns with recognizing sustainable production and consumption patterns as essential for long-term urban sustainability. By reimagining linear business models, companies can establish closed-loop systems that facilitate carbon emission reduction and conserve natural resources, crucial for addressing climate change. This transformation enables businesses to adapt to low-carbon transitions' complexities, leverage innovative technologies, and engage effectively with diverse stakeholders, optimizing resource use and promoting adaptive agility [10, 15, 32].

Social innovation is another significant aspect, addressing social challenges and improving urban populations' well-being. Social enterprises employ innovative strategies to tackle issues like poverty and inequality, contributing to social sustainability and resilience. By integrating these strategies, social enterprises not only alleviate immediate social issues but also foster long-term sustainable development, necessitating collaboration among various stakeholders to navigate the interplay of economic, social, and environmental interests [1, 13]. These enterprises often co-create solutions with local communities, tailoring approaches to specific urban contexts.

Integrating digital technologies into business models transforms company operations and interactions. Data analytics, artificial intelligence, and the Internet of Things (IoT) enhance operational efficiency, decision-making, and resource management. Leveraging big data from sources like web traffic and social media provides insights into market dynamics and consumer behavior, supporting informed strategic choices. Fostering a culture of knowledge sharing amplifies these technological advantages, leading to improved innovation and performance, positioning businesses for sustainable growth in complex environments [17, 19, 15, 9, 26]. These advancements contribute to developing smart urban infrastructures that promote sustainable urban growth.

Platform-based business models, facilitating sharing and collaborative consumption, represent a significant innovation in sustainability. Platforms like ride-sharing and co-working spaces promote resource efficiency and reduce environmental impact by maximizing existing asset utilization. These models offer scalable solutions to urban sustainability challenges, enabling cities to manage growing populations while effectively reducing ecological footprints through standardized assessments and data-driven strategies [5, 8, 6].

6.3 Technological and Socio-Technical Dynamics in Urban Sustainability

Technological and socio-technical dynamics are pivotal in shaping urban sustainability, influencing the development and implementation of innovative solutions for urban agglomerations. Integrating advancements such as Information and Communication Technology (ICT) into urban systems has revolutionized city operations, enabling efficient resource management and enhancing urban life quality [13]. ICT supports creating smart urban infrastructures that optimize energy consumption, transportation systems, and waste management, contributing to carbon emission reductions and sustainable urban growth.

Socio-technical dynamics in urban environments involve interactions between technological systems and social actors, including government agencies, businesses, and local communities. These interactions are vital for successfully implementing sustainability initiatives, significantly affecting urban populations' acceptance and adoption of new technologies. Understanding these dynamics is essential for utilizing social media data and innovative tools to capture the complexities of social-ecological-technological interactions, enhancing decision-making processes aimed at fostering sustainable urban development [8, 19]. Engaging stakeholders in designing and deploying technological solutions ensures responsiveness to urban residents' needs, fostering ownership and commitment to sustainability goals.

Moreover, socio-technical dynamics in urban sustainability underscore the necessity for collaborative governance structures facilitating co-creation of innovative solutions. By fostering partnerships among public, private, and civil society actors, cities can leverage diverse perspectives and expertise to develop comprehensive strategies addressing urban sustainability challenges. This collaborative approach enhances urban systems' resilience, enabling cities to adapt effectively to evolving environmental, social, and economic challenges, particularly amid rapid urbanization and the pressing need for sustainable development in both the global north and south. Integrating diverse perspectives and addressing urban areas' unique characteristics can enhance policy and implementation processes, contributing to a sustainable urban future in the face of climate change and socio-economic disparities [5, 8, 11, 27].

Integrating digital technologies into urban planning and policy-making is also significant for advancing urban sustainability. Utilizing data analytics, artificial intelligence, and IoT enables cities to analyze extensive datasets, including real-time urban geolocated information from social media platforms. This capability provides critical insights into urban dynamics, facilitating evidence-based decision-making that addresses sustainability challenges and enhances urban planning. As cities evolve amid globalization and technological advancements, the ability to analyze diverse data sources becomes increasingly essential for understanding social-ecological interactions and fostering sustainable urban futures [19, 28]. These technologies support developing adaptive urban systems, enhancing sustainability and resilience in urban environments.

7 Discussion

7.1 Comparative Analysis of Urban Sustainability Transitions

A comprehensive analysis of urban sustainability transitions necessitates a multidimensional approach, incorporating diverse methodologies and contextual influences on urban dynamics. Studies on urban complexity and entropy highlight the varied methods used to assess urban systems' complexity [28]. Understanding urban systems' organization and efficiency is crucial for crafting strategies that enhance sustainability. The socio-technical dynamics within smart sustainable cities offer a framework for analyzing these transitions, emphasizing the convergence of technological advancements and social interactions in promoting sustainable urban development [13]. Integrating these dynamics into urban planning and policy-making is essential for developing adaptive and resilient systems.

Contextual antecedents are vital for driving business model innovation, crucial for urban sustainability transitions [15]. The interplay between economic and sustainable factors in entrepreneurship underscores the need for innovative models aligning with sustainability goals [18]. By adopting such models, urban areas can harness economic opportunities to support sustainable development. The choice of analytical techniques significantly impacts understanding urban form and its sustainability implications [25]. Methodological plurality, as highlighted by primal approaches, provides a comprehensive view of urban fabric, enabling researchers to capture urban systems' complexity and devise robust sustainability transition strategies [16].

Strategic alignment among organizational and environmental factors is crucial for achieving competitive advantage in urban sustainability transitions [26]. Tailored strategies are necessary for effective CO2 mitigation in urban areas, addressing their specific characteristics and challenges [7].

7.2 Evaluation of Complexity-Based Approaches

Complexity-based approaches are crucial for analyzing urban sustainability transitions, offering a framework to understand urban systems' intricate interdependencies. Techniques like agent-based modeling (ABM) and system dynamics provide insights into emergent behaviors characterizing urban environments [31]. ABM simulates individual agents' behaviors and interactions, capturing socio-economic dynamics' complexity and non-linear processes driving sustainability transitions. Integrating these approaches with advanced data analytics, such as large language models (LLMs) and machine learning, enhances their application in urban studies. These technologies process vast datasets, identifying patterns and trends that inform urban planning and policy development [6]. The combination of complexity-based modeling and data-driven insights supports developing adaptive urban systems capable of responding to emerging challenges and opportunities, enhancing sustainability and resilience.

Complexity-based approaches are also essential for understanding governance and policy roles in sustainability transitions. By modeling stakeholder interactions and policy interventions' impacts,

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these approaches provide insights into the socio-political dynamics influencing urban development. A comprehensive understanding of challenges and opportunities faced by urban agglomerations, especially in the global south, is crucial for formulating effective policies aligning with sustainability goals and leveraging regional capacities for innovation [5, 8, 6, 27]. Evaluating these approaches underscores the importance of methodological plurality in urban studies. Integrating diverse analytical frameworks enables researchers to capture urban dynamics' full spectrum, offering a holistic perspective on sustainability transitions [16]. This plurality enhances urban analyses' robustness, facilitating the development of targeted strategies promoting sustainable urban growth.

7.3 Implications for Urban Policy and Planning

Recent findings emphasize adopting a comprehensive, interdisciplinary approach to urban policy and planning to facilitate sustainability transitions within urban agglomerations. An integrative approach grounded in core sustainability principles is essential for developing holistic, context-specific strategies [8]. Incorporating these principles allows urban planners to create frameworks aligning with local values and practices, enhancing sustainability initiatives' effectiveness. Accurate representation of urban agglomerations is critical for effective sustainability transitions, informing urban planning and economic modeling for better resource allocation and growth management [24]. Additionally, fostering emotional connections between residents and tourists can enhance community engagement and social cohesion, suggesting that policymakers should prioritize inclusive urban environments [20].

Government support and dynamic capabilities significantly impact green innovative enterprises, implying policymakers should prioritize supportive regulatory frameworks and incentives for innovation in sustainable sectors [2]. This focus can drive low-carbon technologies' adoption, contributing to broader sustainability agendas. Moreover, urban sustainability research must be inclusive, particularly in representing the global south's realities, to address unique challenges and opportunities [5]. Incorporating global south perspectives allows urban policy and planning to better respond to marginalized communities' needs and promote equitable development.

Integrating environmental change factors into urban land models is crucial for understanding urbanization's implications for sustainability and human well-being [3]. Future work should refine frameworks for broader applications and develop user-friendly tools for urban planning and infrastructure management [30]. Additionally, big data analytics can enhance understanding of growth trajectories in technology-based new ventures (TBNVs), providing valuable insights for urban policy and planning [9].

7.4 Socio-Technical Dynamics and Governance

Socio-technical dynamics and governance are integral to facilitating sustainability transitions within urban agglomerations. These dynamics encompass interactions between technological systems and social structures, collectively influencing sustainable urban practices' development and implementation. Effective governance frameworks are essential for coordinating urban stakeholders' interactions, ensuring policies align with sustainability goals while addressing specific urban challenges, particularly in the context of rapid urbanization and climate change resilience [5, 13, 27, 1].

Robust governance structures promote collaboration among stakeholders—including government agencies, private sector entities, and local communities—by fostering an organizational culture that enhances knowledge sharing and drives innovation, ultimately leading to improved performance and successful sustainability transitions [6, 17, 13, 1, 27]. This collaborative approach enables co-creating innovative solutions to urban sustainability challenges. Integrating socio-technical dynamics into governance frameworks enhances cities' capacity to adapt to changing environmental, social, and economic conditions, promoting resilience and sustainability.

Integrating technological advancements, such as Information and Communication Technology (ICT), into urban systems plays a pivotal role in shaping socio-technical dynamics. ICT supports developing smart urban infrastructures for sustainable resource management and improved urban life quality. These technologies facilitate real-time data collection and analysis from diverse sources, including social media, offering critical insights into human behavior and values within urban environments. This information guides decision-making processes and optimizes urban systems, supporting sustainable urban infrastructures and addressing social-ecological-technical interactions' complexities in cities [11, 19].

Governance frameworks must also address sustainability transitions' socio-economic dimensions, ensuring equitable distribution of low-carbon development benefits across urban populations. Implementing comprehensive policies promoting social inclusion and equity, including affordable housing initiatives and improved access to sustainable transportation, is essential for addressing urban sustainability's interrelated challenges and fostering equitable socio-economic development [1, 13]. Prioritizing social equity in governance structures can mitigate potential negative impacts of sustainability transitions on vulnerable populations, fostering resilient and inclusive urban environments.

7.5 Cultural and Contextual Influences

Cultural and contextual influences are crucial in shaping sustainability transitions within urban agglomerations, significantly affecting low-carbon technologies' and practices' adoption and effectiveness. Understanding these influences is vital for urban sustainability assessments, evaluating progress towards sustainable development. As cities become central to global sustainability efforts, recognizing cultural norms, societal practices, and technological adoption interplay can inform better policy-making and strategic planning for effective low-carbon energy transitions. This comprehensive approach underscores the need for mixed-methods research integrating cultural dimensions into sustainability frameworks, guiding urban planners and policymakers through sustainable urbanization's complexities [1, 8, 29]. An urban area's cultural context influences residents' perceptions and attitudes towards sustainability initiatives, affecting community support and engagement. Societies with a strong cultural orientation towards environmental stewardship are more likely to embrace sustainable practices and technologies, facilitating smoother transitions to low-carbon pathways.

Contextual factors, such as economic conditions, governance structures, and social dynamics, also play a critical role in shaping sustainability outcomes. Urban agglomerations in the global south often face unique challenges, such as inadequate infrastructure and social inequalities, necessitating tailored approaches to sustainability transitions [5]. Understanding these contextual nuances is essential for developing strategies responding to different urban areas' specific needs and priorities.

Cultural and contextual influences significantly shape sustainable innovations and technologies' diffusion, impacting their acceptance and implementation within societal and organizational frameworks. Policymakers and energy planners must consider these influences, as they affect strategies promoting low-carbon technologies and practices, ultimately influencing sustainability transitions' overall success [1, 17, 29, 15]. Sustainability initiatives' success often hinges on aligning innovations with local values and practices, highlighting culturally sensitive approaches' importance to urban planning and policy development. By considering cultural and contextual factors, urban planners and policymakers can enhance sustainability transitions' effectiveness, ensuring they are inclusive and equitable.

8 Conclusion

8.1 Methodological Plurality and Future Research Directions

The pursuit of urban sustainability necessitates a multifaceted methodological approach to effectively address the intricate challenges posed by low-carbon transitions. Employing a range of methodologies enriches our comprehension of urban systems and their socio-economic and environmental dynamics, which is crucial for crafting resilient urban development strategies. Future research should prioritize systemic transformations vital for low-carbon advancement, focusing on the integration of market dynamics and global partnerships. Such studies can pinpoint strategic leverage points for policy interventions that drive sustainability transitions. The formulation of comprehensive multi-domain entropy measures offers a promising avenue for evaluating urban resilience and sustainability, providing valuable insights into the organizational efficacy of urban systems.

Empirical investigations into reconfiguration processes across diverse urban settings are essential for refining existing frameworks and enhancing their practical relevance. These should be complemented by longitudinal studies that assess the enduring impacts of contextual factors on business model innovation, thereby enriching our understanding of the drivers behind sustainable practices. Exploring the intersection of culture and technology presents a fertile ground for future exploration, particularly in integrating cultural elements into energy policy and technological design to foster sustainability. Aligning technological innovations with local cultural values can significantly aid the adoption of sustainable technologies.

Additionally, the integration of social values and environmental considerations into ICT applications for urban sustainability remains a pivotal research area. Strategies that align ICT advancements with social and environmental objectives can bolster the efficacy of smart urban infrastructures in achieving sustainability goals. Comparative analyses of just transition policies across various contexts are critical for elucidating the socio-political aspects of low-carbon transitions, uncovering best practices, and informing policy frameworks that support fair and inclusive transitions to low-carbon economies.

Further research should also delve into actual usage behaviors, examining additional factors influencing technology adoption, and exploring alternative T2V models. Investigating dynamic capabilities in resource-constrained environments and expanding datasets to encompass a broader range of countries can deepen our understanding of entrepreneurship's contribution to sustainability.

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