A Survey of Non-radial Directional Distance Function and Global Malmquist-Luenberger Index in Assessing Carbon Emission Performance and Environmental Efficiency in Urban Agglomerations

Abstract

This survey paper explores an advanced analytical framework that integrates non-radial directional distance functions (NDDFs) and the Global Malmquist-Luenberger (GML) productivity index to assess carbon emission performance and environmental efficiency in urban agglomerations. The study underscores the significance of evaluating carbon emissions, given the substantial contribution of urban centers to global greenhouse gas emissions. By accommodating undesirable outputs, NDDFs offer a comprehensive assessment of environmental productivity, crucial for effective policy formulation in urban settings. The integration with the GML index enhances the evaluation of green total factor productivity, offering insights into the interplay between economic growth and environmental sustainability. The paper outlines the methodological framework and discusses case studies illustrating the practical application of these tools. Challenges such as data availability, methodological limitations, and the integration of socioeconomic factors are addressed, highlighting the need for refined methodologies and policy innovations. The findings emphasize the importance of technological advancements and targeted policies in promoting sustainable urban development. By leveraging these methodologies, urban planners and policymakers can develop effective strategies to enhance environmental efficiency, supporting the transition towards sustainable urban futures.

1 Introduction

1.1 Importance of Assessing Carbon Emission Performance

Assessing carbon emission performance in urban agglomerations is crucial for sustainable development, as these areas contribute approximately 70% of global greenhouse gas emissions [1, 2]. The rapid growth of urban populations and infrastructures amplifies the need for effective assessment mechanisms [3]. Understanding carbon emissions is essential for monitoring productivity changes and evaluating the environmental impacts of urban growth [4]. Such evaluations are vital for developing strategies that enhance environmental efficiency and align with international sustainability goals, including China's commitment to carbon neutrality by 2060 [5].

Urban sprawl often results in inefficient land use and increased environmental degradation, underscoring the necessity of assessing carbon emission performance to mitigate these adverse effects [6]. The COVID-19 pandemic has further highlighted the importance of these assessments, as shifts in industrial activity necessitate a reevaluation of environmental impacts across various sectors [4]. Additionally, evaluating carbon emissions is critical for addressing socioeconomic disparities, such as the unequal distribution of household carbon footprints in Europe, which has significant implications for equitable carbon policy and sustainability [7].

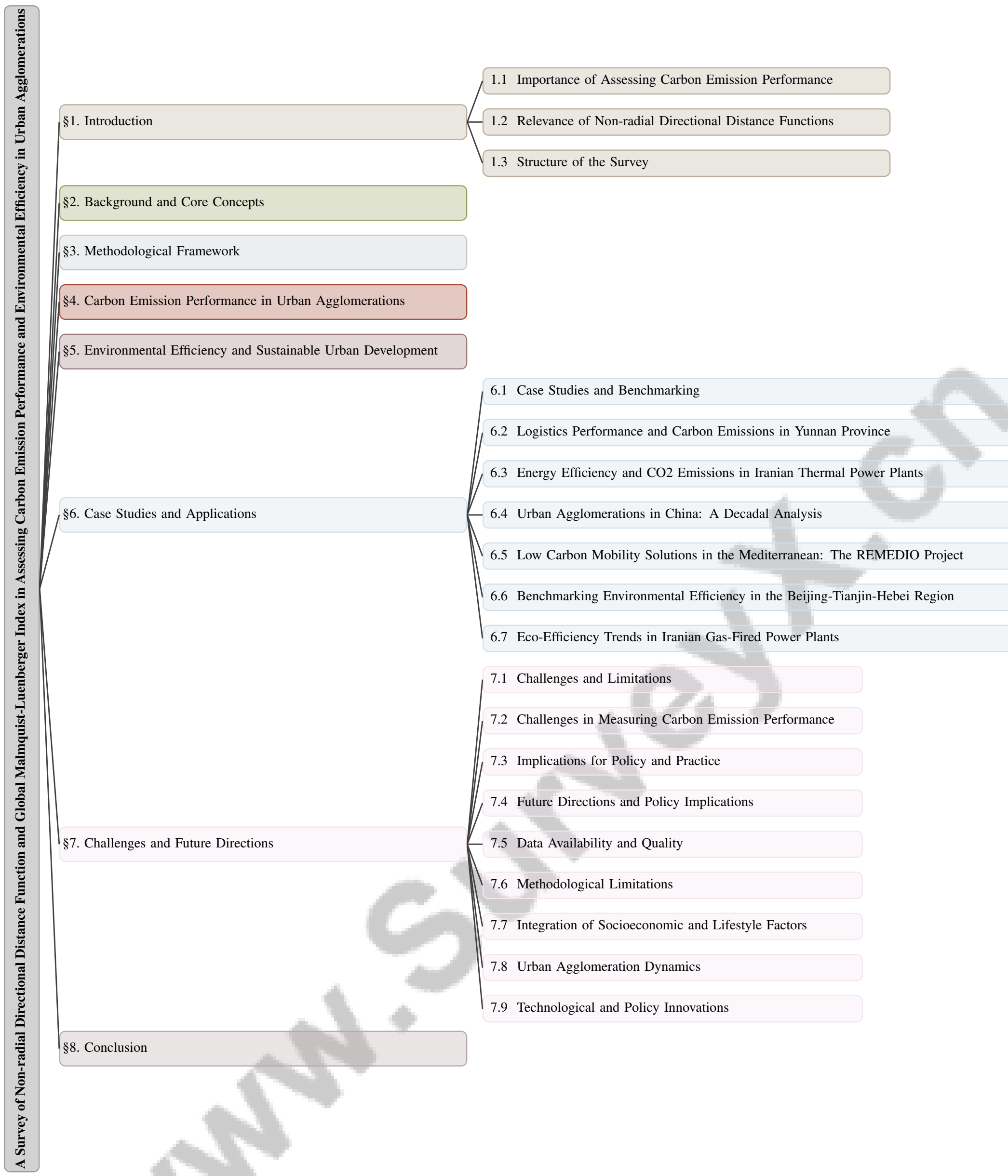

Figure 1: chapter structure

The interconnectedness of sectoral performance and broader environmental objectives is evident in productivity changes within the water industry [8]. The high greenhouse gas emissions associated with cement and concrete production also necessitate assessments to promote eco-friendly alternatives, such as chitosan for soil stabilization [9]. As urban agglomerations expand, the relationship between city size and emissions becomes increasingly significant, requiring comprehensive evaluations to maintain urban quality and manage carbon dioxide emissions [6].

In China, the development of urban agglomerations has driven industrialization and urbanization, leading to high energy consumption and pollution emissions, which highlights the importance of assessing carbon emission performance to guide sustainable development policies [5]. Effective measurement of green total factor productivity (GTFP) is necessary to understand the relationship between economic growth and environmental sustainability, further emphasizing the need for precise carbon emission assessments [2]. The industrial sector's development significantly impacts resource consumption and environmental pollution, as observed in regions like Jiangxi Province [4].

The comprehensive evaluation of carbon emission performance in urban agglomerations is integral to addressing the multifaceted challenges of sustainable development. These assessments shape effective urban policy design, enhance resource allocation efficiency, and facilitate the achievement of decarbonization targets, all essential for confronting the sustainability challenges posed by rapid urbanization and climate change, given that cities are responsible for a substantial portion of global greenhouse gas emissions and are increasingly vulnerable to environmental impacts [10, 3, 11, 12, 13].

1.2 Relevance of Non-radial Directional Distance Functions

Non-radial directional distance functions (NDDFs) are essential for performance measurement, particularly in evaluating environmental efficiency and carbon emissions. Unlike traditional radial models, NDDFs accommodate multiple outputs, including undesirable ones, thus providing a comprehensive assessment framework [2]. This capability is particularly relevant in urban agglomerations, where the complex interplay among various sectors and environmental factors must be considered. Integrating NDDFs with Data Envelopment Analysis (DEA) and the Malmquist-Luenberger index offers a robust approach to evaluating both static and dynamic carbon emission performance, surpassing earlier benchmarks that focused solely on expected outputs [9].

By incorporating undesirable outputs into productivity analysis, NDDFs facilitate a nuanced understanding of environmental productivity. This is especially pertinent in urban contexts, where distinguishing between persistent and transient components of carbon emissions is vital for effective policy formulation [4]. Moreover, NDDFs enable a comprehensive evaluation of resource efficiency across various sectors, extending their applicability beyond traditional industrial contexts. The proposed method utilizing a modified NDDF to assess CO2 emission performance underscores the importance of accounting for technology heterogeneity, which is crucial for accurate performance assessments among diverse entities, such as ports [4].

The versatility of NDDFs emphasizes their significance in performance measurement, as they allow for the assessment of energy efficiency while accounting for undesirable outputs. Integrating NDDFs into frameworks that combine smart city and sustainable city concepts further enhances urban sustainability. Consequently, NDDFs are instrumental in advancing sustainable development in urban agglomerations by capturing the complexity of environmental interactions and supporting the integration of undesirable outputs. Additionally, the blockchain framework known as the carbon footprint chain (CFC) can complement NDDFs by ensuring accurate recording and verification of carbon footprint data while maintaining stakeholder privacy [7].

1.3 Structure of the Survey

This survey provides a comprehensive analysis of the methodologies and applications of non-radial directional distance functions and the Global Malmquist-Luenberger index in assessing carbon emission performance and environmental efficiency within urban agglomerations. It begins with an introduction that emphasizes the importance of evaluating carbon emissions and the relevance of non-radial directional distance functions in this context. The subsequent section, Background and Core Concepts, explores the fundamental theories and interconnections among core concepts, laying the groundwork for methodological exploration.

In the Methodological Framework section, we examine the integration of non-radial directional distance functions with the Global Malmquist-Luenberger index, detailing how this synergistic framework enhances the assessment of environmental efficiency. The survey then analyzes Carbon Emission Performance in Urban Agglomerations, investigating current emission levels, influential factors, and the global impact of urban centers on carbon footprints.

The focus shifts to Environmental Efficiency and Sustainable Urban Development, discussing the conceptualization of environmental efficiency and its critical role in promoting urban sustainability. The Case Studies and Applications section presents empirical evidence and practical insights through diverse case studies, demonstrating the real-world implications of the discussed methodologies. These case studies span various sectors and regions, such as the Mediterranean area, where a comprehensive carbon footprint estimation methodology was applied to research project activities, revealing that on-site events significantly contribute to overall emissions. Best practices for reducing carbon footprints, such as promoting public transportation and hybrid events, are highlighted as effective strategies for substantial emissions reductions. Furthermore, the exploration of AI's environmental impact underscores the need for sustainable practices in technology development, illustrating the pressing requirement for responsible innovation across multiple domains [14, 6, 3].

The penultimate section, Challenges and Future Directions, identifies current limitations and proposes future research avenues to refine assessment tools and enhance policy implications. The Conclusion synthesizes key findings, emphasizing the significance of the integrated analytical framework in fostering sustainable urban development by improving carbon emission performance and environmental efficiency.The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Global Malmquist-Luenberger Index

The Global Malmquist-Luenberger (GML) index is a pivotal tool in evaluating environmental performance, especially within urban agglomerations. It uniquely incorporates both desirable and undesirable outputs, such as carbon emissions, into productivity analyses, offering a nuanced evaluation of efficiency and productivity changes over time [15, 4]. This index provides a comprehensive understanding of environmental productivity, reflecting the economic and environmental dynamics inherent in urban settings.

By assessing Green Total Factor Productivity (GTFP), the GML index integrates energy inputs and environmental pollution, establishing a robust framework for evaluating urban environmental efficiency [15]. This is crucial for decomposing productivity across urban agglomerations and informing policy implications. The GML index's integration with methodologies like the lexicographic Directional Distance Function (DDF) and the smallest improvement DDF enhances its application by computing efficient targets and minimal improvements, respectively [16]. This ensures thorough analyses essential for developing strategies to mitigate environmental impacts and foster sustainable urban development.

The GML index's versatility extends to various sectors, including urban sustainability and resilience assessments, analyzing urban morphology, compactness, and height [14]. This holistic approach is essential for addressing decarbonization challenges, particularly in high-emission industries like cement production [1]. By providing a comprehensive evaluation of productivity and environmental performance, the GML index informs policies aimed at reducing carbon footprints and enhancing environmental efficiency [8].

Additionally, incorporating the Material Balance Principle into the GML index, as demonstrated by the MBP Malmquist Luenberger Index, allows for more precise eco-efficiency assessments in sectors such as power generation [17]. This slacks-based model enhances performance assessment precision, supporting the formulation of targeted strategies for improving environmental outcomes. Through its comprehensive approach, the GML index deepens understanding of urban environmental challenges and aids in creating policies that promote sustainable growth and resource conservation.

2.2 Interrelationship and Significance in Urban Agglomerations

The interrelationship between the Global Malmquist-Luenberger (GML) index, non-radial directional distance functions, and urban agglomerations is crucial for enhancing environmental efficiency and carbon emission performance. Urban agglomerations, with dense populations and extensive economic activities, present unique challenges and opportunities for sustainable development [15]. The GML index, by incorporating undesirable outputs such as carbon emissions, serves as a comprehensive tool for assessing environmental efficiency and addressing inefficiencies in total factor productivity growth rates, particularly in densely populated and industrially active coastal areas [4].

In urban contexts, population density and economic activity significantly contribute to increased carbon footprints [8]. The framework connecting urban compactness with agglomeration economies highlights the impact of density and boundary limitations on sustainability [4]. Larger cities, while economically productive, often exhibit disproportionately higher CO2 emissions compared to smaller urban centers, necessitating targeted interventions to mitigate environmental impacts [15]. The GML index and non-radial directional distance functions offer robust methodologies for analyzing these dynamics, integrating undesirable outputs to facilitate a nuanced understanding of urban environmental challenges [8].

Unsustainable high-carbon lifestyles in urban populations, such as those in Japan, reveal significant discrepancies between current carbon footprints and decarbonization targets. This issue is exacerbated by the challenges of accurately predicting future urban populations and understanding the implications of urbanization on infrastructure and sustainability [8]. Research categorization into fields like urban crime, socioeconomic inequalities, and public health further underscores the interconnectedness of these issues in urban agglomerations [4].

Electricity generation in thermal power plants, particularly in regions such as Iran, is a major source of greenhouse gas emissions, raising concerns about environmental degradation and the need for cleaner energy solutions [15]. The integration of the GML index with non-radial directional distance functions facilitates comprehensive assessments of such sectors, enabling policymakers to devise strategies aligned with sustainability goals [4]. By treating emissions as undesirable outputs, the GML index and related methodologies provide critical insights into the environmental efficiency of urban agglomerations, supporting the development of policies aimed at reducing carbon footprints and promoting sustainable urban growth.

3 Methodological Framework

Category	Feature	Method
Synergistic Framework for Urban Agglomerations	Environmental Evaluation	MNDDF[4], GML[15], CML[8]

Table 1: This table presents the synergistic framework for evaluating carbon emission performance and environmental efficiency in urban agglomerations, integrating Non-Radial Directional Distance Functions (NDDFs) and the Global Malmquist-Luenberger (GML) index. It highlights the methods used for environmental evaluation, providing a comprehensive approach to assess urban sustainability and productivity growth.

The methodological framework for evaluating carbon emission performance and environmental efficiency is crucial to understanding urban agglomerations' complexities. Table 1 details the methodological framework employed for environmental evaluation in urban agglomerations, emphasizing the integration of Non-Radial Directional Distance Functions and the Global Malmquist-Luenberger index. Additionally, Table 2 presents a comparative overview of the methodological frameworks for evaluating environmental efficiency in urban agglomerations, focusing on the integration of Non-Radial Directional Distance Functions and a synergistic framework. This section emphasizes integrating Non-Radial Directional Distance Functions (NDDFs), which are vital for assessing urban sustainability and environmental efficiency across diverse urban settings. As illustrated in **??**, the hierarchical structure of this framework highlights the integration of NDDFs within a synergistic approach tailored for urban agglomerations. Key components depicted in the figure include systematic approaches, analytical enhancements, policy implications, and comprehensive methodologies that collectively contribute to sustainable urban development. The following subsections detail these methodologies, further elucidating their role in enhancing urban environmental performance assessments.

3.1 Integration of Non-Radial Directional Distance Functions

The integration of Non-Radial Directional Distance Functions (NDDFs) into the analytical framework for evaluating carbon emission performance and environmental efficiency involves a systematic approach utilizing multiple data dimensions. This process begins by identifying Decision-Making Units (DMUs), such as cities or provinces, and collecting relevant input-output data necessary for performance evaluation [8]. The NDDF methodology effectively incorporates both desirable and undesirable outputs, offering a comprehensive assessment of environmental efficiency.

NDDFs are adept at analyzing the complex relationships between economic activities and their environmental impacts, crucial for urban agglomerations. By defining DMUs and their inputs and outputs, NDDFs facilitate a nuanced understanding of efficiency dynamics within urban contexts [8]. This is achieved by projecting DMUs onto the efficient frontier using both exogenous and endogenous directional vectors, thus enhancing efficiency assessments by accounting for technological and operational variations across urban areas.

Moreover, combining NDDFs with the Global Malmquist-Luenberger (GML) index enriches the analytical framework, enabling the measurement of green total factor productivity (GTFP) while considering energy inputs and undesirable outputs like carbon emissions. This combined methodology is essential for assessing the environmental efficiency of decision-making units over time, aiding the formulation of targeted strategies for sustainable urban development. By systematically comparing results from standard and novel approaches using a comprehensive country-level database on air pollutants [8], this methodology provides a robust tool for understanding urban agglomerations' complex dynamics.

The application of NDDFs in evaluating urban efficiencies is exemplified by studies examining the relationship between urban compactness indicators and environmental performance. Through regression analyses and advanced statistical techniques, researchers rigorously investigate how urban form and population density impact carbon emissions and resource consumption. This research is vital for informing policy decisions aimed at enhancing sustainability in urban agglomerations, particularly given evidence that larger cities exhibit a superlinear scaling relationship between population size and carbon emissions, indicating disproportionately high environmental costs [12, 18]. Understanding these dynamics is essential for urban planners and policymakers navigating the complexities of future urbanization, shaped by evolving technological, economic, and lifestyle factors throughout the 21st century. This comprehensive approach facilitates a detailed analysis of efficiency trends and supports effective strategies for promoting sustainable urban development.

3.2 Synergistic Framework for Urban Agglomerations

The synergistic framework combining Non-Radial Directional Distance Functions (NDDFs) and the Global Malmquist-Luenberger (GML) index offers a comprehensive method for evaluating carbon emission performance and environmental efficiency in urban agglomerations. This framework leverages both methodologies to deliver a holistic assessment of urban sustainability, capturing the complexities of economic activities and their environmental impacts [4]. By integrating NDDFs, which account for multiple outputs including undesirable ones, with the GML index, which measures green productivity growth, the framework enables nuanced analysis of urban environmental dynamics and productivity changes over time [15].

This combined framework is significant for urban agglomerations, allowing policymakers to identify inefficiencies and areas for improvement through detailed assessments of both static and dynamic aspects of environmental performance. The framework's capacity to incorporate undesirable outputs, such as carbon emissions, into productivity assessments is particularly vital in urban contexts, where the interplay between industrial activities and environmental sustainability is intricate and multifaceted [8]. Furthermore, integrating NDDFs and the GML index supports the development of targeted strategies that align with sustainability goals, enhancing urban resilience and promoting sustainable growth [4].

The synergistic framework also facilitates cross-sectional and longitudinal analyses of urban agglomerations, enabling benchmarking of environmental efficiency and productivity across different regions and time periods. By providing insights into the relationship between urban form, density, and environmental performance, the framework aids in formulating policies aimed at reducing carbon footprints and improving resource utilization in urban areas [8]. This comprehensive approach ensures that urban planners and decision-makers can devise effective strategies for sustainable urban development, addressing challenges posed by rapid urbanization and climate change [15].

Integrating Non-Radial Directional Distance Functions (NDDFs) and the Global Malmquist-Luenberger (GML) index within this synergistic framework represents a substantial advancement in evaluating environmental efficiency and carbon emission performance across urban agglomerations. It enhances the assessment of logistics-related carbon emissions and identifies driving factors influencing green productivity growth in major cities, contributing to more informed policymaking for sustainable urban development [19, 20, 5, 21, 22]. This framework serves as a robust tool for evaluating the complex dynamics of urban environments, supporting the development of policies and strategies that foster sustainable urban futures.

Feature	Integration of Non-Radial Directional Distance Functions	Synergistic Framework for Urban Agglomerations
Integration Approach	Systematic Data Utilization	Holistic Method Leveraging
Evaluation Focus	Urban Efficiency Dynamics	Sustainability And Productivity
Output Consideration	Desirable And Undesirable	Multiple Including Undesirable

Table 2: This table provides a comparative analysis of two methodological frameworks for evaluating environmental efficiency in urban agglomerations. It highlights the integration approach, evaluation focus, and output consideration of Non-Radial Directional Distance Functions and a synergistic framework leveraging multiple outputs, including undesirable ones. The table underscores the differences in systematic data utilization and holistic methods for assessing urban sustainability and productivity.

4 Carbon Emission Performance in Urban Agglomerations

4.1 Current State of Carbon Emissions

The variability in carbon emissions across urban agglomerations is shaped by technological, economic, and infrastructural factors. A study of air pollutants from 39 countries between 1995 and 2007 highlights emission disparities and the detrimental impact of undesirable outputs on environmental performance [8]. Similarly, Iranian gas-fired power plants show performance variations over eight years, reflecting the influence of technological advancements and trade-offs on emissions [17].

Sectoral performance and environmental goals further complicate emissions in urban areas. Productivity changes in sectors like the water industry reveal diverse carbon emission performance levels [8]. Technological change significantly drives productivity and green growth in urban regions. Diverse emission profiles across urban agglomerations necessitate tailored regional strategies. For instance, panel data from China highlights inefficiencies in static green growth efficiency, indicating areas needing intervention to boost green total factor productivity (GTFP) [8]. Mediterranean studies stress the need for integrated assessments considering both economic and environmental factors [8].

Innovative methods, such as using chitosan for soil stabilization, demonstrate potential improvements in emission performance tailored to specific contexts [8]. Addressing carbon emissions in urban agglomerations demands nuanced assessments and strategies aligned with regional characteristics, technological progress, and economic activities to effectively reduce emissions and promote sustainable urban development.

4.2 Factors Influencing Carbon Emissions

Carbon emissions in urban areas are influenced by economic, technological, and infrastructural elements. Urban sprawl, leading to inefficient land use, increases emissions due to higher energy demands from dispersed layouts [23]. This often results in greater reliance on automobiles, exacerbating emissions. Compact urban forms, however, promote lower emissions by reducing travel distances and enhancing public transport efficiency.

Technological advancements play a crucial role in shaping emissions. Energy-efficient technologies in industrial and transportation sectors can reduce emissions by optimizing energy use and minimizing waste. The adoption of cleaner production processes and renewable energy is critical for curbing emissions and advancing sustainable urban development [8]. The transition to smart city concepts, leveraging digital technologies, can enhance resource management and reduce energy consumption.

Economic activities within urban agglomerations also impact emissions. The density and scale of industrial activities, along with industry types, dictate emission levels. Regions with energy-intensive industries, like the Beijing-Tianjin-Hebei area in China, experience elevated emissions due to inefficient green innovation and coal reliance [14, 6, 19, 9, 22]. Conversely, areas focused on service-oriented or high-tech industries may exhibit lower emissions due to reduced energy demands.

Socioeconomic factors, including income levels and lifestyle choices, significantly affect emissions. Higher incomes often correlate with increased consumption and energy use, contributing to greater emissions. High-carbon lifestyles elevate urban carbon footprints. Research shows that the top 10

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4.3 Role of Urban Agglomerations in Global Carbon Footprint

Urban agglomerations significantly influence the global carbon footprint due to concentrated populations, economic activities, and resource consumption. These areas serve as hubs for industrial production, transportation, and energy consumption, contributing to substantial emissions [4]. The economic dynamism and industrial outputs of urban agglomerations often lead to increased greenhouse gas emissions, driven by energy and resource demands essential for urban life [8].

Urban expansion correlates with higher energy consumption and waste generation, exacerbating emissions. Urban sprawl, characterized by low-density development, leads to increased vehicular travel and energy use, elevating the carbon footprint [23]. In contrast, compact urban forms that promote efficient land use and public transportation can mitigate these effects by reducing reliance on private vehicles and enhancing energy efficiency.

Urban agglomerations are also centers of innovation and technological advancement, influencing their carbon footprint. Adopting smart city technologies and sustainable planning practices can reduce emissions by optimizing energy use, improving waste management, and enhancing public transport systems [8]. These innovations are crucial for transitioning towards low-carbon urban development and achieving global sustainability goals.

Socioeconomic characteristics of urban populations, including income levels and consumption patterns, impact urban agglomerations' carbon footprint. High-income urban residents often exhibit larger carbon footprints due to increased consumption of energy-intensive goods and services [8]. Addressing these disparities through equitable policy measures and promoting sustainable consumption practices are essential for reducing urban areas' carbon footprint.

5 Environmental Efficiency and Sustainable Urban Development

5.1 Conceptualizing Environmental Efficiency

Environmental efficiency is pivotal for sustainable urban development, reflecting the ability of urban systems to optimize resource utilization while minimizing environmental impacts, particularly carbon emissions. This concept is closely linked to Green Total Factor Productivity (GTFP), which evaluates the effectiveness of sustainability management within economic frameworks by incorporating both static and dynamic performance aspects and accounting for undesirable outputs [24, 5]. Innovative materials and technologies, such as substituting lime and cement with chitosan, can significantly reduce carbon emissions, underscoring the importance of green innovation in enhancing environmental performance [25, 9].

Accurate urban boundary definitions are crucial to prevent biases in emissions data that could distort environmental efficiency assessments [18]. Urban compactness enhances environmental efficiency, as denser urban forms promote economic efficiencies by reducing energy consumption and emissions through optimized land use and transportation systems that favor public transit over private vehicles [23]. In energy production, benchmarks for thermal power plants in Iran provide insights into changes in green productivity and efficiency, highlighting the need for continuous innovation in sustainable energy practices [26, 21].

Advanced technologies and data-driven approaches are critical for improving environmental efficiency. AI systems that minimize operational and embodied carbon footprints exemplify technology's potential in achieving sustainability goals [14]. Blockchain frameworks, like the carbon footprint chain (CFC), facilitate scalable, privacy-preserving data tracking, supporting efficient environmental data management [7]. Environmental efficiency is a cornerstone of sustainable urban development, requiring a multifaceted approach involving innovative materials, precise data, and advanced technologies. By optimizing resource use and implementing greenhouse gas reduction measures, urban areas can enhance environmental performance, significantly contributing to global sustainability initiatives. Given that urban populations are projected to exceed two-thirds of the global total by 2050, addressing these challenges is critical. Comprehensive reforms rooted in local institutions and context-sensitive data are necessary to ensure cities meet the needs of growing populations while effectively contributing to climate resilience and sustainability goals [11, 18, 13].

5.2 Factors Influencing Environmental Efficiency

Environmental efficiency in urban settings is influenced by technological, economic, infrastructural, and policy-driven factors. Technological advancements play a crucial role by enabling cleaner production processes and enhancing the energy efficiency of urban infrastructures [4]. Innovations in renewable energy technologies and energy-efficient building designs significantly reduce urban carbon footprints and improve resource utilization [15]. Economic factors, such as the structure and scale of urban economies, also impact environmental efficiency. Urban areas with service-oriented industries often exhibit better environmental performance compared to those reliant on resource-intensive heavy industries [8]. The economic resilience and diversification of urban economies influence their capacity to adopt sustainable practices and technologies.

Infrastructural elements, including urban form and transportation systems, are critical determinants of environmental efficiency. Compact urban designs promoting high-density development and efficient public transport systems can significantly lower energy consumption and emissions by reducing reliance on private vehicles [23]. The integration of smart city technologies into urban planning further enhances environmental efficiency by optimizing resource management and minimizing waste [7]. Policy frameworks and governance structures are essential in shaping environmental efficiency. Effective environmental policies that promote sustainable practices, incentivize green technologies, and enforce regulatory standards are crucial for enhancing urban sustainability [4]. Collaborative governance models involving multiple stakeholders facilitate the implementation of comprehensive strategies for improving urban environmental performance.

Socioeconomic factors, such as income levels and lifestyle choices, further influence environmental efficiency. Higher income levels often correlate with increased consumption patterns, leading to greater resource use and emissions. Addressing these disparities through equitable policy measures and promoting sustainable consumption practices is vital for mitigating urban environmental impacts [8]. The determinants of environmental efficiency in urban areas are intricately interconnected, necessitating a comprehensive strategy integrating technological innovation, economic restructuring, infrastructure development, and robust policy frameworks. This approach is essential for addressing the complexities outlined in the urban sustainable development goal (USDG), emphasizing the need for inclusive, safe, resilient, and sustainable cities. It must also consider challenges related to indicator selection and data collection for effective monitoring, as well as the unique characteristics of different urban contexts. By fostering collaboration among local institutions and utilizing context-sensitive data, cities can better navigate the interplay of compact development and agglomeration economies, ultimately promoting sustainable urban growth while mitigating adverse effects of urbanization [11, 10, 23].

6 Case Studies and Applications

This section examines the link between environmental efficiency and urban sustainability through case studies utilizing advanced methodologies like non-radial directional distance functions (NDDFs) and the Global Malmquist-Luenberger (GML) index. These examples provide insights into the practical application of these tools for assessing environmental performance in diverse urban contexts, focusing on enhancing sustainability initiatives.

6.1 Case Studies and Benchmarking

NDDFs and the GML index offer crucial insights into environmental efficiency and carbon emissions across urban agglomerations. These methods evaluate efficiency and productivity, revealing regional disparities influenced by technological and policy factors. NDDFs optimize decision-making units on a production frontier, while the GML index enables dynamic efficiency analysis over time, evaluating environmental policies' impact on urban energy production and consumption [28, 2]. A notable case is the Iranian thermal power plants' assessment using NDDFs, which highlights technological trade-offs affecting carbon emissions and establishes benchmarks for eco-efficiency improvements [17]. In China, the GML index assesses green total factor productivity, identifying inefficiencies in rapidly industrializing regions and suggesting targeted sustainability interventions [8]. Urban compactness analyses further inform policy by correlating form and density with emissions and resource use [23]. Mediterranean studies integrate NDDFs and the GML index to balance economic activities with environmental impacts, providing comprehensive insights for policy development [8].

Benchmark	Size	Domain	Task Format	Metric
PENACC:ES[27]	35	Energy Efficiency	Performance Evaluation	Efficiency Score, CO2 Emissions
MLP[26]	56	Energy Production	Efficiency Measurement	Malmquist-Luenberger Index, Efficiency Change
GML[21]	561	Environmental Economics	Productivity Measurement	GML, GM
Super-EBM[9]	1,000,000	Manufacturing	Efficiency Measurement	Malmquist-Luenberger index, Super-EBM model

Table 3: Table illustrating key benchmarks used in the evaluation of environmental efficiency and productivity across various domains. The table summarizes the size, domain, task format, and metrics of different benchmarks, highlighting their relevance in assessing energy efficiency, production, and environmental economics.

These methodologies have also been applied to logistics, resource-based cities, and port enterprises, revealing performance variations and key factors influencing carbon emissions [19, 6, 5, 4]. Table 3 provides an overview of significant benchmarks employed in the analysis of environmental efficiency and productivity, emphasizing their application in diverse domains such as energy efficiency and environmental economics.

6.2 Logistics Performance and Carbon Emissions in Yunnan Province

Yunnan Province exemplifies the balance between economic growth and environmental sustainability, particularly in logistics. From 2011 to 2015, logistics-related carbon emissions rose, highlighting the need for improved performance [14, 6, 19, 4, 29]. Yunnan's logistics infrastructure is vital for trade efficiency, yet traditional transport modes elevate emissions. NDDFs and the GML index assess logistics eco-efficiency, incorporating carbon emissions into evaluations. Strategies focus on optimizing networks, adopting cleaner technologies, and promoting intermodal solutions, aligning with low-carbon goals [14, 8, 30, 6]. Rail and waterway transport development and smart logistics systems further enhance efficiency and reduce emissions.

6.3 Energy Efficiency and CO2 Emissions in Iranian Thermal Power Plants

Iranian thermal power plants are crucial for energy demands but significantly contribute to CO2 emissions, necessitating efficiency improvements [17]. Using NDDFs, eco-efficiency assessments incorporate electricity and CO2 outputs. Over eight years, technological advancements have influenced eco-efficiency, guiding cleaner technology adoption and resource optimization. Benchmarking against international standards identifies improvement areas [17]. The GML index enhances analysis by measuring green productivity growth, informing policies to reduce power generation's environmental impact [17].

6.4 Urban Agglomerations in China: A Decadal Analysis

A decade-long analysis of Chinese urban agglomerations reveals carbon emissions and environmental efficiency trends, shaped by industrial structures, technological advancements, and policy interventions [4]. High industrial activity correlates with higher emissions, while service-oriented economies perform better environmentally [8]. Cleaner production technologies and energy-efficient practices have reduced emissions, supporting carbon neutrality goals [5]. Smart city concepts further enhance resource management. Policy interventions, such as regulatory standards and compact urban forms, have improved environmental efficiency [23]. However, regional disparities necessitate tailored strategies for consistent sustainability improvements [8].

6.5 Low Carbon Mobility Solutions in the Mediterranean: The REMEDIO Project

The REMEDIO project promotes low carbon mobility in the Mediterranean, addressing urban transport sustainability. By implementing strategies to reduce emissions, the project leverages smart city research and carbon footprint methodologies [10, 6, 13]. Best practices include public transport and soft mobility, reducing carbon footprints significantly. The Mediterranean's diverse urban landscapes present unique challenges and opportunities. The project engages stakeholders to develop sustainable mobility strategies, promoting active transport modes and integrating smart technologies for optimized networks [8]. Community engagement fosters ownership and responsibility for sustainable transport initiatives.

6.6 Benchmarking Environmental Efficiency in the Beijing-Tianjin-Hebei Region

The Beijing-Tianjin-Hebei (BTH) region, a major economic hub, faces environmental efficiency challenges due to industrial activity and urbanization. NDDFs and the GML index assess environmental efficiency, incorporating carbon emissions into comprehensive evaluations [4]. Results reveal disparities driven by industrial structure, technology, and policy. Beijing, with service-oriented industries, often outperforms Tianjin and Hebei [4]. Technological change and policy interventions, like regulatory standards and public transport systems, enhance efficiency [23]. These strategies mitigate urban sprawl and promote sustainable development.

6.7 Eco-Efficiency Trends in Iranian Gas-Fired Power Plants

Eco-efficiency trends in Iranian gas-fired power plants, analyzed via the Malmquist-Luenberger method, highlight the impact of fuel type and operations on environmental performance [14, 6, 17, 3, 26]. These plants play a key role in electricity supply, yet contribute to emissions. NDDFs evaluate eco-efficiency, incorporating electricity and CO2 outputs [17]. Technological advancements and policy interventions have driven improvements, but challenges remain due to disparities in technology and infrastructure [27, 14, 22, 26]. Targeted strategies are needed to enhance performance across the sector.

7 Challenges and Future Directions

Exploring the challenges and future directions in urban environmental efficiency and carbon emission performance reveals a multifaceted landscape influenced by numerous factors. As urban agglomerations expand, understanding these intricacies is vital for effective policy formulation and implementation. The following subsections address specific challenges and limitations in this field, emphasizing methodological hurdles and data-related issues faced by researchers and policymakers in evaluating environmental performance. Addressing these challenges can establish more robust frameworks and innovative solutions to enhance urban sustainability.

7.1 Challenges and Limitations

Assessing environmental efficiency and carbon emission performance in urban agglomerations presents methodological challenges that affect the accuracy and applicability of current frameworks. A significant limitation is the dependence on extensive data and computational resources required by methods like the Global Malmquist-Luenberger (GML) index, which becomes burdensome for larger systems, restricting practical implementation [16]. Additionally, the availability and accuracy of data for undesirable outputs complicate comprehensive environmental assessments [15].

The fragmentation between core and peripheral cities within urban agglomerations complicates efforts to achieve integrated environmental efficiency improvements, resulting in weak synergistic mitigation effects [6]. Current benchmarks often fail to consider regional differences in energy infrastructure and economic conditions, limiting the generalizability of findings across diverse urban contexts [5]. Furthermore, subjective semantic labels influenced by cultural variances lead to inconsistencies in urban classification [7], undermining reliability when applying standardized methodologies across regions.

The Malmquist-Luenberger Productivity Index (MLPI) faces challenges such as infeasibility issues when computing cross-period directional distance functions, limiting analyses to countries with feasible solutions [8]. Existing methods often overlook variables influencing productivity, indicating challenges in applying the analytical framework to broader contexts [22]. Reliance on available data, which may not encompass all environmental factors or account for technological advancements and variations in fuel types, leads to incomplete assessments of green productivity and environmental efficiency, particularly in regions with underdeveloped energy statistics [6]. Moreover, focusing

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solely on CO2 emissions, without considering other greenhouse gases, limits the comprehensiveness of environmental evaluations [9].

These challenges underscore the urgent need for a systematic approach to data collection, the development of improved methodological frameworks, and the incorporation of diverse urban dynamics. Enhancements are essential for accurately assessing environmental efficiency and carbon emission performance, particularly as cities contribute significantly to global greenhouse gas emissions and face increasing vulnerabilities due to climate change. Addressing these issues can better align urban policy with sustainability goals, facilitating transformative solutions that consider resilience and ecological integrity [10, 11, 19, 21, 13].

7.2 Challenges in Measuring Carbon Emission Performance

Measuring carbon emission performance in urban agglomerations entails challenges due to complex interactions among environmental and infrastructural factors. Potential clustering of chitosan fibers at higher dosages can affect soil cohesion and stability, influencing carbon emission assessments [25]. The heterogeneity of urban infrastructures and diversity of economic activities complicate the standardization of measurement frameworks. Variations in industrial processes, energy consumption patterns, and technological adoption across urban areas lead to discrepancies in carbon emission data, complicating consistent performance benchmarks. Studies on carbon emissions in Yunnan Province and U.S. cities illustrate substantial variability due to differing factors, highlighting the need for tailored methodologies that account for local factors [19, 6, 30, 18].

Integrating undesirable outputs, such as carbon emissions, into performance measurement frameworks is complicated by data availability and quality. Data on emissions is often incomplete or inaccurate, especially in regions with less developed environmental monitoring systems, hampering thorough evaluations of carbon emission performance, particularly in sectors like logistics [19, 6]. The dynamic nature of urban environments, characterized by rapid changes in population density, infrastructure development, and economic activities, necessitates adaptive measurement approaches. Traditional models, such as the standard Malmquist-Luenberger index, often fail to incorporate dynamic factors, leading to inaccuracies in performance assessments [31, 17, 8, 6, 21].

Comprehensive methodologies that integrate critical factors such as material properties, data quality, and the dynamic characteristics of urban environments are essential. This approach enhances the reliability of emissions assessments and aligns with best practices identified in studies, highlighting the impact of transportation choices and event organization on carbon footprint reduction [19, 6, 13].

7.3 Implications for Policy and Practice

The findings regarding carbon emission performance and environmental efficiency in urban agglomerations have profound implications for policy and urban management. The integration of non-radial directional distance functions (NDDFs) and the Global Malmquist-Luenberger (GML) index provides a robust framework for assessing environmental performance, informing the development of targeted policies aimed at enhancing urban sustainability [4]. By incorporating undesirable outputs, such as carbon emissions, into productivity assessments, policymakers gain a nuanced understanding of the environmental challenges urban agglomerations face, enabling the formulation of more effective mitigation and adaptation strategies [15].

A practical implication is the necessity for policies promoting technological innovation and cleaner production processes. Findings emphasize investing in renewable energy technologies and energy-efficient practices to reduce emissions and improve environmental efficiency [17]. Policymakers should consider incentives for industries to adopt green technologies and implement best practices in resource management, supporting a transition towards low-carbon urban development.

Urban planning and design play a crucial role in shaping environmental outcomes. Compact urban forms and efficient public transportation systems reduce energy consumption and emissions, suggesting that urban planners should prioritize sustainable land use and transportation planning [23]. Policies encouraging smart cities, leveraging digital technologies to optimize urban operations, further enhance resource efficiency and reduce impacts [8].

Addressing socioeconomic disparities in urban areas is essential for equitable carbon reduction. Higher income levels are often associated with increased consumption patterns and energy use,

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leading to greater emissions [8]. Policymakers should implement measures promoting sustainable consumption practices and support low-income communities in accessing energy-efficient technologies, ensuring inclusive and equitable carbon reduction efforts.

7.4 Future Directions and Policy Implications

Future research on carbon emission performance and environmental efficiency in urban agglomerations should prioritize developing refined methodologies to address existing limitations and enhance sustainability outcomes. A promising area of exploration is integrating innovative technologies and methodologies that bolster sustainability practices, particularly in urban development, aligning with potential future research directions for improving environmental efficiency [3]. Enhancing data collection methods and expanding the indicator system are crucial for refining assessments of land-sea coordination and urban sustainability [15].

Enhancing green productivity methodologies should focus on innovative agricultural technologies and policies addressing regional disparities in productivity, providing a nuanced understanding of environmental efficiency across diverse urban settings, facilitating targeted interventions [8]. Future research should also explore refinements to existing methods and their application across different sectors and pollutants to enhance robustness [8].

Addressing methodological challenges associated with the Malmquist-Luenberger Productivity Index (MLPI), future research should refine this framework to resolve infeasibility issues and explore the impacts of specific policy measures on environmental productivity. Applying the MBP Malmquist Luenberger Index in other industries and integrating additional environmental factors could enhance model comprehensiveness and inform policy decisions [17].

Further research should consider developing alternative cements and enhancing carbonation processes, alongside creating policies incentivizing sustainable practices in the construction sector. Exploring the relationship between urban size and other greenhouse gases, as well as refining methods to include additional environmental factors, is another critical area for future exploration [8].

Integrating Information and Communication Technology (ICT) in urban planning to foster sustainable urban transformations presents another avenue for future research, necessitating comprehensive frameworks to facilitate this process. Enhancing data collection methods and exploring additional dimensions of integrated development will further refine assessments and support sustainable urban growth [15].

In the realm of AI, developing frameworks for carbon accounting and methodologies for optimizing carbon footprints are essential future research directions. Extending research to include additional pollutants and human capital factors will enhance the assessment of industrial sustainability. Refining methodologies for different research projects and exploring the variability of emission sources across geographic areas will also be crucial [8].

Future research should focus on refining the evaluation index system and exploring additional factors influencing green growth efficiency in oil and gas resource-based cities. Developing energy-efficient AI models and establishing standards for measuring and reporting AI's environmental impact are also critical. Finally, exploring the extension of methods to centralized DEA contexts and integrating them with interval or fuzzy data could enhance their applicability [17].

The future research directions and policy implications emphasize the critical necessity for a comprehensive and flexible strategy to improve environmental efficiency in urban agglomerations. This approach is essential for facilitating the transition towards sustainable urban development, particularly as urban areas are responsible for a significant portion of global greenhouse gas emissions and increasingly vulnerable to climate change impacts. As urbanization continues to rise, with projections indicating that over 60% of the global population will live in cities by 2030, adopting innovative and resilient solutions to address the complex interplay of sustainability challenges inherent in urban settings is imperative. A clear understanding of the distinct yet interconnected concepts of urban sustainability and resilience is crucial to avoid confusion that can hinder transformative efforts [12, 13].

7.5 Data Availability and Quality

Data availability and quality are critical factors influencing the assessment of environmental efficiency and carbon emission performance in urban agglomerations. The accuracy and comprehensiveness of data used in these assessments directly affect the reliability of results and subsequent policy implications. A primary challenge is the limited availability of accurate data across different provinces, which can hinder effective evaluation of environmental performance [32]. This limitation is often exacerbated by inconsistent regional classifications, leading to discrepancies in data interpretation and analysis.

Moreover, the quality of data concerning undesirable outputs, such as pollution, poses significant challenges for accurately assessing environmental efficiency [24]. In many cases, data on pollution and other undesirable outputs may be incomplete or inaccurate, particularly in regions with less developed environmental monitoring systems. This deficiency can result in skewed assessments of environmental performance, as omitting critical variables may lead to underestimating or overestimating actual environmental impacts.

Integrating advanced data collection methods and technologies is essential for overcoming these challenges and improving data quality. Enhanced monitoring systems and standardized data reporting protocols can facilitate the collection of comprehensive and accurate data, thereby supporting more reliable assessments of environmental efficiency and carbon emissions. Refining the classification of urban regions and integrating a more comprehensive array of environmental indicators can significantly improve data granularity and precision. This enhancement allows for nuanced analyses of urban sustainability, addressing critical challenges identified in the implementation of the United Nations Urban Sustainable Development Goal (USDG), such as the limited availability of standardized data and the need for context-specific applications by diverse local actors. By anchoring these efforts in robust local institutions and inclusive data collection practices, we can better monitor and promote sustainable urban development amidst the complexities of urbanization and environmental change [11, 3].

Addressing data availability and quality challenges is essential for enhancing the evaluation of environmental efficiency and carbon emission performance in urban agglomerations, particularly as cities, responsible for approximately 70% of global greenhouse gas emissions and home to over 4 billion residents, face increasing pressure to implement sustainable practices. Effective monitoring and assessment of urban sustainability initiatives can only be achieved through standardized, open, and reliable data, which is necessary for informed decision-making and policy implementation aimed at achieving the United Nations Sustainable Development Goals by 2030 [11, 19, 21, 13]. By improving data collection and ensuring the accuracy of environmental metrics, researchers and policymakers can develop more effective strategies for promoting sustainable urban development and mitigating climate change impacts.

7.6 Methodological Limitations

The methodologies used to assess environmental efficiency and carbon emission performance in urban agglomerations, while robust, have limitations. A significant constraint is the reliance on the Global Malmquist-Luenberger (GML) index and non-radial directional distance functions (NDDFs), which necessitate extensive data inputs and computational resources. This requirement can be particularly challenging for large-scale applications across numerous urban divisions, potentially limiting practical implementation [16]. Additionally, the GML index may encounter infeasibility issues when computing cross-period directional distance functions, restricting its applicability to regions where feasible solutions exist [8].

Another limitation is the difficulty in accurately incorporating undesirable outputs, such as carbon emissions, into performance assessments. The availability and quality of data for these outputs are often inadequate, particularly in regions with underdeveloped environmental monitoring systems. This data deficiency can lead to incomplete assessments and may not fully capture the dynamic nature of urban environments [15]. Furthermore, existing methodologies may not account for all variables influencing productivity, indicating potential gaps in the comprehensive evaluation of environmental performance [22].

The integration of NDDFs with the GML index, while offering a comprehensive framework for evaluating environmental efficiency, may not fully address the heterogeneity of urban infrastructures and economic activities. Variations in industrial processes, energy consumption patterns, and technological adoption across different urban areas can result in discrepancies in performance evaluations, complicating the establishment of consistent benchmarks [4].

Moreover, the methodologies often rely on subjective semantic labels that vary by culture, undermining the reliability of environmental assessments when applied across different regions [7]. This cultural variability presents challenges in standardizing methodologies and ensuring consistency in urban classification. Additionally, manual calibration processes and the inability to differentiate between vehicle types in vehicle counting algorithms further limit the accuracy of urban emissions assessments [1].

These methodological limitations underscore the pressing need for continuous refinement and adaptation of existing urban sustainability frameworks. This is essential to enhance their applicability and reliability across diverse urban contexts, particularly as cities confront complex challenges related to rapid urbanization, climate change vulnerability, and socioeconomic inequalities. By addressing ambiguities in the definitions of urban sustainability and resilience and improving data collection and monitoring processes, policymakers can better navigate the intricate dynamics of urban environments and contribute to achieving global sustainability goals [10, 11, 33, 12, 13]. By addressing these limitations, researchers can improve the robustness of environmental efficiency assessments and support the development of more effective strategies for sustainable urban development.

7.7 Integration of Socioeconomic and Lifestyle Factors

Integrating socioeconomic and lifestyle factors into the assessment of environmental efficiency and carbon emission performance in urban agglomerations is essential for developing a comprehensive understanding of sustainability challenges and opportunities. Socioeconomic variables, such as income levels, education, and employment, significantly influence consumption patterns and energy use, impacting carbon emissions and environmental efficiency [4]. Higher income levels often correlate with increased consumption of energy-intensive goods and services, leading to larger carbon footprints [8]. Future research should explore the relationship between socioeconomic status and environmental outcomes to identify targeted interventions promoting equitable sustainability practices.

Lifestyle factors, including transportation habits, dietary choices, and housing preferences, also play a crucial role in shaping urban carbon emissions. High-carbon lifestyles, characterized by reliance on private vehicles, meat-heavy diets, and energy-intensive housing, exacerbate environmental impacts in urban areas [8]. Understanding the interplay between lifestyle choices and environmental performance is vital for developing policies that encourage sustainable behaviors and reduce urban carbon footprints.

Moreover, integrating socioeconomic and lifestyle factors into environmental assessments can enhance the accuracy and relevance of sustainability metrics. By incorporating these variables into existing frameworks, researchers can better account for the diverse influences on urban environmental efficiency and develop more comprehensive strategies for mitigating climate change [15]. This approach necessitates the collection of detailed socioeconomic and lifestyle data, which can be used to refine models and improve the precision of environmental evaluations.

7.8 Urban Agglomeration Dynamics

The dynamics of urban agglomerations are characterized by complex interactions among economic activities, population density, infrastructure development, and environmental impacts. These dynamics significantly influence the efficiency and emissions of urban areas, shaping their sustainability trajectories. Urban agglomerations, as concentrated hubs of economic and social activities, present unique challenges and opportunities for sustainable development [4].

A critical aspect of urban agglomeration dynamics is the interplay between population density and resource utilization. High-density urban areas often benefit from agglomeration economies, leading to increased productivity and efficiency through shared infrastructure and services [8]. However, these benefits are accompanied by heightened environmental pressures, as densely populated areas typically exhibit higher energy consumption and emissions due to concentrated economic activities and transportation demands [15].

The spatial configuration of urban agglomerations also plays a crucial role in determining their environmental efficiency. Compact urban forms, characterized by mixed-use developments and efficient public transportation systems, can mitigate the adverse effects of urban sprawl by reducing reliance on private vehicles and promoting sustainable mobility [23]. In contrast, sprawling urban areas with low-density development patterns often experience increased emissions and resource inefficiencies due to the extended infrastructure and transportation networks required to support dispersed populations [4].

Technological advancements and policy interventions are vital in shaping the dynamics of urban agglomerations and their environmental outcomes. Integrating smart city technologies and sustainable urban planning practices can enhance resource management and reduce emissions by optimizing energy use and improving waste management [8]. Additionally, policies promoting green technologies and sustainable land use can support the transition towards low-carbon urban development, aligning with global sustainability goals [15].

Socioeconomic factors, including income disparities and lifestyle choices, further influence the dynamics of urban agglomerations. Higher income levels often correlate with increased consumption patterns and energy use, contributing to larger carbon footprints in urban areas [8]. Addressing these disparities through equitable policy measures and promoting sustainable consumption practices are essential for reducing the environmental impact of urban agglomerations and enhancing their overall efficiency.

7.9 Technological and Policy Innovations

Technological and policy innovations are pivotal in enhancing urban environmental efficiency, offering pathways to sustainable urban development by addressing the complex challenges posed by rapid urbanization and climate change. Integrating smart city technologies, leveraging digital tools and data analytics, optimizes urban operations, reduces energy consumption, and minimizes waste, significantly improving environmental efficiency [8]. These technologies facilitate real-time monitoring and management of urban resources, enabling cities to respond dynamically to environmental challenges and optimize their infrastructure and services.

The adoption of renewable energy technologies is another critical innovation that can substantially reduce carbon emissions in urban areas. Transitioning to clean energy sources, such as solar, wind, and bioenergy, decreases reliance on fossil fuels, thus lowering the carbon footprint of urban agglomerations [15]. Policy frameworks that incentivize deploying renewable energy infrastructure and support research and development in clean technologies are essential for accelerating this transition and achieving sustainability targets.

Policy innovations complement technological advancements by creating regulatory environments that promote sustainable practices and technologies. Policies enforcing strict emission standards, providing subsidies for green technologies, and encouraging energy-efficient building designs can drive significant improvements in urban sustainability [4]. Moreover, developing comprehensive urban planning policies prioritizing compact development, mixed land use, and efficient public transportation systems can mitigate the adverse effects of urban sprawl and enhance resource efficiency [23].

Integrating Information and Communication Technology (ICT) in urban planning offers additional opportunities for improving environmental efficiency. ICT-enabled solutions, such as smart grids and intelligent transport systems, enhance the efficiency of energy distribution and transportation networks, reducing energy consumption and emissions [8]. Furthermore, using blockchain technology for transparent and secure data management can facilitate tracking carbon footprints and support implementing effective sustainability measures [7].

8 Conclusion

The exploration of non-radial directional distance functions alongside the Global Malmquist-Luenberger index underscores their pivotal role in assessing carbon emission performance and environmental efficiency within urban agglomerations. These methodologies provide a robust framework by incorporating both desirable and undesirable outputs, thus offering a comprehensive understanding of urban environmental dynamics and productivity evolution. The research emphasizes

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the critical need for improving production efficiency to enhance the impact of environmental policies, thereby advancing sustainable urban development.

The study highlights the importance of implementing targeted interventions and policy reforms to address high-carbon lifestyles, as various consumer groups currently exceed the carbon footprint benchmarks set for 2030 and 2050. Recognizing the potential of alternative data sources is crucial for enriching the understanding of urban dynamics, thereby supporting the advancement of sustainable urban development. Moreover, the successful implementation of the Urban Sustainable Development Goal framework relies heavily on local institutional involvement and the adaptation of indicators to meet specific urban needs.

The integration of technological advancements with innovative policy measures is vital for enhancing urban environmental efficiency, especially given the increasing trend of urban concentration and its implications for infrastructure and sustainability strategies. The findings advocate for policies that support green agricultural practices, reflecting the broader necessity for comprehensive strategies that harmonize economic growth with environmental sustainability.

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