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Research Progress on Carbon Emissions

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ABSTRACT

Driven by the “dual-carbon” goals and the intensifying global climate-governance agenda, carbon-emission research has evolved into a core interdisciplinary theme. Using a narrative literature-review approach, we map the intellectual trajectory of this field through three lenses: accounting methods, driving factors and mitigation pathways. Methodologically, a dual accounting system has emerged that separately tracks production-based and consumption-based emissions. Factor studies concentrate on the interplay among economic growth, energy structure, technological progress and policy regulation.Mitigation options span energy substitution, industrial upgrading, carbon capture/utilization/storage (CCUS) and other technologies, as well as policy instruments such as carbon markets and carbon taxes; trans-regional cooperative mitigation is gaining momentum. Key gaps remain: micro-level behavioural drivers are poorly understood, cross-scale accounting interfaces are weak, and the quantitative coupling effects of technology-policy packages lag behind. Future work should integrate multiple methods, foster cross-disciplinary collaboration and enhance dynamic simulation to deliver precise mitigation insights.

INTRODUCTION

Global climate change has become a critical worldwide threat to human survival and development. The escalating frequency of extreme climate events, which has triggered ecological degradation, food security crises and other related issues, has led countries to reach a consensus on the regulation of greenhouse gas emissions. [1]. The 2015 Paris Agreement locked in the hard target of “holding warming to 1.5°C”[2]; China unveiled its “dual-carbon” strategy in 2020; and the 2021 Glasgow Climate Pact intensified globally coordinated mitigation. As these international accords and national strategies move from pledge to implementation, carbon emissions have shifted from an environmental-science topic to a cross-cutting determinant of economic and social development, emerging as a central interdisciplinary research theme. Systematically charting the evolution and frontiers of carbon-emission studies under this backdrop is therefore of paramount theoretical and practical value for designing precise mitigation policies and refining carbon-governance systems.The evolution of carbon emission research is deeply intertwined with the process of global climate governance, undergoing a logical progression from "emission quantification" to "mechanism analysis" and further to "emission reduction optimization." Early work concentrated on constructing accounting methods — life-cycle assessment [3], emission-factor approaches [4] and other techniques—to deliver accurate measurements at regional, sectoral and corporate scales, thereby furnishing the baseline data needed for target setting. As the core tool for quantifying greenhouse-gas releases, carbon accounting underpins carbon management, emissions trading and policy design; its scientific rigor directly determines the precision of mitigation pathways [5]. Meanwhile, international rules such as the EU’s Carbon Border Adjustment Mechanism (CBAM) are forcing accounting standards to converge with global norms, and digital transformation is opening new avenues for methodological innovation.

As research matured, scholars shifted attention to the driving forces of carbon emissions, deploying STIRPAT [6], LMDI [7] and allied models to estimate the mitigation elasticity of population growth, economic development, technological

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progress and other factors, thereby identifying critical leverage points for emission cuts.At present,Carbon emission research exhibits a characteristic of multi-dimensional expansion: in terms of research scale, it has formed full-scale coverage spanning "global—national — regional — urban — enterprise"; in terms of research content, it integrates theories from multiple fields such as energy economics, industrial transformation, and technological innovation to explore the synergistic pathways between emission reduction and development; In terms of research methodology, big data and machine learning technologies are employed to enhance the accuracy of emission forecasting and policy simulation.Yet outstanding problems However, existing studies still face challenges such as inadequate regional adaptability of accounting systems, unclear cross-scale emission transmission mechanisms, and quantification biases in technological emission reduction potential. Against this backdrop, we systematically review advances in carbon accounting, driving mechanisms and mitigation pathways, dissect existing limitations and chart future research directions, offering a theoretical compass for global climate governance and the attainment of the “dual-carbon” target.

1.Carbon-emission accounting

Accurate accounting is the prerequisite for any in-depth analysis of carbon emissions. Viewed through the lens of responsibility, two complementary approaches exist: production-based accounting and consumption-based accounting [8].

1.1.Production-based accounting

Grounded in the “polluter-pays” principle, this method attributes all emissions generated within a given territorial boundary to the jurisdiction where the goods or services are produced. It therefore creates a direct incentive for local producers to improve energy efficiency. Three main techniques are used [9]:

(1) Emission-factor method

Introduced by the IPCC in its first Revised Guidelines for National Greenhouse Gas Inventories (1996), this approach equates emissions with the product of activity data and an emission factor for each source category①.

Equation:GHG emissions = Activity data × Emission factor

The method is simple, transparent and scalable, making it the work-horse for national-, provincial- and city-level inventories [10].

(2) Mass-balance method

This technique tracks carbon inflows and outflows for each process or device. By comparing the carbon content of inputs (feedstock, fuels) with that of outputs (products, wastes), it yields the net CO_2 released.

Equation:CO_2 emissions = (Input mass × C content – Product mass × C content – Waste mass × C content) × 44/12

The method is especially useful for benchmarking individual installations or verifying whether new equipment meets emission standards [11].

(3) Direct measurement (stack-testing) method

Here, flue-gas velocity and CO_2 concentration are measured on site and converted to mass emissions.

Equation:CO_2 emissions = Gas velocity × CO_2 concentration × Unit-conversion factor

Although this gives the highest temporal and spatial resolution, it requires costly high-precision analyzers and is limited to point sources. In practice, samples are often collected in the field and analyzed in certified laboratories, so representativeness and instrument accuracy remain critical uncertainties [12].

1.2.Consumption-based accounting

This approach quantifies the emissions embodied in imported and exported goods—commonly termed the “carbon footprint.” By tracing greenhouse gases along global value chains, it reveals the climate impacts driven by consumers rather than producers, thereby informing equitable mitigation strategies and honoring the principle of “common but differentiated responsibilities” [13].

Numerous studies have employed input–output (IO) techniques to map consumption-based emissions at global [14-17], national [18-19] and regional [20-23] scales, highlighting how international trade redistributes carbon burdens. Country-level analyses now exist for Australia [24], China [25], Italy [26], the UK [27] and others. Recent work further refines the method: Kander et al. (2015) [29] advocate adjusting IO tables for sectoral technology

①See https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/.

differences among exporters, yielding footprint estimates that more accurately predict how national policy shifts propagate through global supply chains. Such consumption-side metrics complement conventional production inventories and offer decision-makers an forward-looking gauge of their policies' worldwide emission consequences.

2.Identifying the drivers of carbon emissions

Decomposing the forces behind emissions has long been a core theme in the literature. Two analytical families dominate: Structural Decomposition Analysis (SDA) and Index Decomposition Analysis (IDA). The key difference is that SDA is built on input–output tables, whereas IDA requires only sector-aggregated data. Hoekstra et al. (2003) show that SDA's richer data requirement is offset by its ability to capture both direct and indirect effects—e.g., how a demand shift in one sector propagates through the entire production network—something IDA cannot detect [30].Among IDA variants, the Logarithmic Mean Divisia Index (LMDI) has become the work-horse model thanks to its solid theoretical foundation, adaptability, lack of residual term and transparent results [31-32].

Recent applications illustrate the expanding research frontier:Liu et al. (2024) couple STIRPAT with scenario analysis for 30 Chinese provinces, decomposing eight drivers into "policy-expected" variables (population, per-capita GDP, urbanization) and "policy-controlled" levers (energy mix, efficiency, industrial structure, transport structure, R&D). They find population, affluence, urbanization and innovation to be the dominant positive drivers, whereas industrial upgrading, energy intensity decline, fuel switching and transport optimization yield significant mitigation [33].Xu et al. (2017) show that economic growth governs sectoral CO_2 emissions, with industrialization exerting a stronger effect in central China than in the east or west. Urbanization's impact weakens as human-capital accumulation and private-car ownership diverge across regions, while the energy-structure effect migrates west-to-east, producing region-specific outcomes [34].Motinho (2015) documents a Europe-wide shift toward lower-carbon final energy consumption, but highlights pronounced spatial and temporal heterogeneity [35].

3.Mitigation pathways

Current studies converge on four complementary tracks:

3.1.Policy & regulatory track

Di et al. (2016) deploy the LEAP model to evaluate Argentina's climate-control policies, projecting energy-efficiency gains and CO_2 trajectories for the energy sector through 2050 [36]. Kadian et al. (2007) apply the same platform to Delhi's residential sector, comparing policy packages and technology choices for reducing household energy use and GHG emissions [37].

3.2.Fiscal & financial track

Hu et al. (2019) couple LEAP with cost-optimization for Shenzhen, demonstrating that sustainable-energy planning can meet municipal CO_2 targets at minimum economic cost [38]. Emodi et al. (2017) run scenario simulations for Nigeria, balancing energy-demand, supply, emissions and cost-benefit metrics to identify fiscally viable low-carbon pathways [39].

3.3.Industrial & energy-structure track

Tao et al. (2011) construct baseline, low-carbon and slow low-carbon scenarios for China out to 2050, driven by per-capita GDP, energy use, energy mix and CO_2 emissions. They find that renewable-energy diffusion, industrial restructuring, efficiency gains and clean-energy development are the most effective levers for achieving a low-carbon economy [40].

3.4.Technology & R&D track

Dehdar et al. (2022) analyze 36 OECD countries (1994-2015), showing that while GDP, fossil-fuel use, industrialization and tax-to-GDP ratios exacerbate emissions, urbanization, environmental patents and environmental-tax shares significantly cut CO_2 [41]. Cheng et al. (2024) demonstrate that upgrading the technology-innovation value chain accelerates green transition [42]. You, Khattak & Ahmad (2024) argue that international R&D cooperation on green technologies enables China to co-develop innovations that raise energy efficiency and lower CO_2 simultaneously [43].

Conclusion

Industrial carbon emissions, their influencing factors, and mitigation pathways constitute a core research agenda in global climate change studies, with a comprehensive "accounting-driving-impact-regulation" framework having been established. As one of the primary sources of carbon emissions, the industrial sector's emission fluctuations directly shape the trajectory of global climate change.Scholars worldwide have produced a rich body of work that is both inspiring and instructive. Yet the deepening of international climate governance, accelerating industrial restructuring and imminent technological revolutions expose critical gaps. No consensus exists on a universal accounting standard; driver and pathway studies abound, but province-level evidence is still sparse. The absence of an agreed, scalable accounting method now constrains further advances in quantification, driver analysis and pathway design. Future research must therefore embrace multi-disciplinary integration, target key scientific questions and deliver systemic innovation in perspectives, methods and content.

(1)In Terms of Research Perspective

It is necessary to deepen the shift from "macro total quantity" to "micro precision" and strengthen multi-scale coupling analysis. Existing studies mainly focus on macro scales such as countries and provinces, while lacking precise accounting and analysis of driving mechanisms at micro scales like parks, enterprises, and products, leading to a disconnect between macro policies and micro practices. In the future, a multi-scale linked research system of "macro-medium-micro" should be constructed:

At the macro level, it is essential to refine the regional decomposition mechanism under the nationally determined contributions (NDCs), integrate the connection between the "dual carbon" goals and global climate agreements, and improve the dynamic simulation of carbon emission peaks and carbon neutrality paths.

At the meso level, the focus should be on key units such as industrial clusters and industrial parks to analyze the carbon emission transfer laws in industrial linkages.

At the micro level, relying on enterprise production data and life cycle assessment (LCA) methods, precise traceability of carbon emissions throughout the product life cycle should be realized to provide targeted schemes for enterprise carbon management.

(2)In Terms of Research Methodology

It is imperative to promote the integration of "traditional econometrics" and "digital technologies" to enhance the precision and predictability of research. Existing studies mostly rely on econometric models and statistical data, which struggle to address the complexity and dynamics of carbon emission systems. In the future, full use should be made of digital technologies such as big data, artificial intelligence, and the Internet of Things:

Based on multi-source data from satellite remote sensing and ground monitoring stations, build a real-time monitoring and dynamic accounting platform for carbon emissions to solve the problems of data lag and large errors in traditional accounting.

Use machine learning algorithms to optimize models for identifying carbon emission driving factors, improving the ability to capture implicit driving factors such as technological progress and consumption upgrading.

Combine system dynamics (SD) and Agent-Based models to simulate carbon emission evolution paths under different policy scenarios, enhancing the scientificity and forward-looking nature of policy formulation.

(3)In Terms of Research Content

Focus should be placed on "emerging fields" and "key issues" to strengthen problem-oriented innovative research:

Pay attention to the carbon emission characteristics of emerging industries and new-type urbanization, analyze the dual impacts of new economic forms such as the digital economy and platform economy on carbon emissions, and clarify the core mechanism of green technological innovation in emission reduction.

Deepen the interactive research between carbon emissions and the climate system as well as the ecological environment, quantify the impacts of carbon emissions on extreme climate events and biodiversity, and construct a research chain of "carbon emissions-ecological response-risk early warning".

Improve the research on cross-border and regional carbon emission transfer. Combined with international cooperation initiatives such as the "Belt and Road Initiative", analyze the carbon emission transfer laws in the global value chain, providing theoretical support for building a fair and reasonable global climate governance system.

Additional Research Orientations

(3)Furthermore, it is necessary to strengthen the research orientation of "policy implementation" and "interdisciplinary integration". In the future, efforts should be made to:

Enhance research on the evaluation and optimization of carbon emission policies, quantify policy implementation effects using methods such as quasi-natural experiments, and address problems like the "one-size-fits-all" approach and "rebound effect" in policy execution.Furthermore, research priorities should emphasize both policy implementation and interdisciplinary integration. Future studies should intensify evaluations and optimizations of carbon emission policies, utilizing quasi-natural experiments to quantify policy effectiveness while addressing issues like one-size-fits-all approaches and rebound effects. By fostering deep integration among environmental science, economics, management, and computer science, we can overcome the complexity of carbon emission systems and provide more targeted theoretical frameworks and technical solutions for global climate governance and regional carbon peaking and neutrality (dual carbon) initiatives.

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