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Review

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A review of household carbon footprint: measurement methods, evolution and emissions assessment

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Abstract
The escalating concern over environmental issues stemming from global climate change is noteworthy. With the rapid pace of urbanization and industrialization, residential consumption has increasingly contributed to carbon emissions, posing an environmental challenge that demands attention. This paper presents a comprehensive overview of measurement methods, evolution, and assessment of household carbon footprints. It delves deeply into the concept of carbon footprints and measurement techniques, and examines the impacts of economic and social factors as well as consumption behaviors on household carbon footprints. The article introduces carbon footprint assessment models and tools suitable for individual up to city-level applications. It also thoroughly discusses the challenges related to data quality, model construction, and parameter selection in the assessment process, while offering insights into future research directions. By synthesizing interdisciplinary research findings, this article proposes a multidimensional and multi-level framework for assessing household carbon footprints, providing scientific guidance for policy formulation, environmental protection actions, and public participation. It aims to foster the transition of society towards a low-carbon and sustainable development model.

Keywords: Carbon footprints, household consumption, measurement methods, structural evolution

INTRODUCTION

Climate change is one of the major challenges of our time, bringing immense pressure[1] to our society and environment, which has garnered widespread attention from countries and regions worldwide. The rapid advancement of the global economy and persistent population growth have expedited the processes of industrialization and urbanization, resulting in a continual surge in energy consumption and carbon emissions, exacerbating the velocity and scope of climate change[2]. This change has had a significant impact on natural systems and socioeconomic systems[3,4]. Climate change is not only a significant challenge of our time but also a stark reality that human society must address.

In order to achieve emission reduction targets, society must undergo rapid and profound transformations across all sectors. Among these sectors, households stand out as significant energy consumers, responsible for approximately 30%-40% of overall greenhouse gas emissions resulting from electricity and heat use[5]. Moreover, upon conducting a thorough examination of the data, it becomes evident that the household sector alone contributes 17% of total global carbon dioxide (CO_2) emissions[6]. Recent studies have highlighted the significance of sustainable urban development strategies and carbon mitigation policies in addressing climate change. These studies have emphasized the necessity for a detailed understanding of the interconnections between economic activity, spatial planning, and carbon emissions[7,8]. Recognizing the pivotal role of households in mitigating global climate change and implementing impactful measures is paramount[9-11]. Within the realm of social sciences, there is a burgeoning body of literature dedicated to exploring methods to reduce carbon emissions by influencing the behaviors and lifestyles of individuals and families. Many scholars advocate for this approach, considering it essential and potent in climate change mitigation[12-14]. Therefore, the examination of household carbon footprints holds particular importance and scientific significance in this context.

A carbon footprint is the aggregate greenhouse gas emissions resulting from both direct and indirect sources by a person, organization, event, or product. The household carbon footprint is a key metric for assessing GHG emissions from residential consumption. The objective of this paper is to comprehensively summarize the relevant research findings on household carbon footprints regarding measurement, comparison, and evaluation. Numerous academic studies have been undertaken on carbon footprint analysis. Initially, research on carbon footprints focused on defining their significance and environmental impact in relation to greenhouse gas emissions. As research advances, scholars are increasingly directing their focus towards exploring measurement methods and tools relevant to this field. The foundational groundwork for calculating and assessing carbon footprints was established through the early contributions of Rees[15] and Wackernagel *et al.*[16]. Subsequently, additional scholars have further refined the methods, tools, and frameworks associated with this field[17-19].

In recent years, there has been a growing interest in researching household carbon footprints, encompassing various aspects, with notable advancements particularly in measurement, comparison, and evaluation. Researchers have conducted surveys and data analyses to initially identify variations in carbon footprint levels among different regions and demographics[20,21], examining them at both macro levels, such as national and regional scales, and micro levels, including individual households[22,23]. These efforts have significantly contributed to a comprehensive understanding of the sources, influencing factors, and impacts of household carbon emissions. Furthermore, a multitude of studies have concentrated on investigating the intricate relationship between household carbon footprints and influential factors such as economic development and social structure[24-26]. These studies aim to explore viable approaches for mitigating carbon footprints and assessing the feasibility of policy implementation[27].

While substantial advancements have been made in the extant literature regarding household carbon footprint measurement, assessment frameworks, and macro- and micro-level analyses, several notable deficiencies and constraints persist. Primarily, existing research frequently lacks comprehensive theoretical exploration and critical analysis of household carbon footprint measurement methods, resulting in constraints and ambiguities in the practical implementation of certain methods. Additionally, current studies often disregard the suitability of household carbon footprint measurement methods in diverse socioeconomic contexts, thereby constraining their efficacy and utility in practical policy development.

This study aims to address this research gap by introducing novel theoretical frameworks and methodologies to achieve a more precise and comparable assessment in the realm of household carbon footprint measurement. Our intention is to critically evaluate the limitations of current household carbon footprint measurement methods, with a specific emphasis on potential biases in data collection and processing, and to investigate how these biases might impact the ultimate measurement outcomes. Concurrently, we will delve into the suitability of household carbon footprint measurement methods across various socioeconomic contexts, aiming to offer insights for the development of context-specific mitigation policies. Building upon this foundation, our study will move beyond mere horizontal comparisons, adopting a multidimensional analytical approach to explore the intricate relationship between household carbon footprints and socioeconomic factors. Through this comprehensive analytical framework, we anticipate gaining a deeper comprehension of the dynamics of household carbon footprints and the influencing factors, thereby providing theoretical underpinnings and empirical evidence to inform the development of more scientific, systematic, and comprehensive emission reduction strategies.

The paper is structured as follows. In Section "THE CONCEPT AND MEASUREMENT METHODS OF CARBON FOOTPRINT", various methods of measuring household carbon footprints are systematically summarized, covering both direct and indirect calculation approaches, along with the use of diverse models and tools. Section "ANALYSIS OF FACTORS INFLUENCING HOUSEHOLD CARBON FOOTPRINT" examines the development of household carbon footprint structures, analyzing the influencing factors and their trends. Section "METHODS AND TOOLS FOR ASSESSING HOUSEHOLD CARBON FOOTPRINT" summarizes the relevant research findings on household carbon emission assessment, encompassing data collection, model construction, and parameter selection, while assessing the implications of these findings for formulating policies to reduce carbon emissions. Sections "CHALLENGES AND PROSPECTS OF HOUSEHOLD CARBON FOOTPRINT ASSESSMENT" and "DISCUSSION" present the research findings of this paper, outline future research directions and recommendations for household carbon footprint studies, and offer insights and suggestions for policy formulation.

THE CONCEPT AND MEASUREMENT METHODS OF CARBON FOOTPRINT

The definition and connotation of carbon footprint

The continuous increase in human activities has led to a rise in the concentration of greenhouse gases in the atmosphere, severely disrupting ecosystems and the natural environment, triggering global climate change and a series of adverse effects. Before formulating scientifically effective emission reduction policies, it is essential to accurately assess the amount of greenhouse gases emitted by human activities. Therefore, carbon footprint, as an important tool for measuring greenhouse gases, has attracted widespread attention and discussion across various sectors of society. It can effectively reflect the level of pressure that specific human activities or products impose on the ecological environment, thus becoming one of the focal points of research in recent years.

In 1992, the Canadian ecological economist Rees proposed the concept of "Ecological Footprint[15]", which became an important branch of the "footprint family[28,29]". The Ecological Footprint is quantified in global hectares and denotes the land and sea area with bioproductive capacity necessary to support a particular population[30]. In accordance with this concept, the Carbon Footprint signifies the land area needed to sequester all the carbon dioxide produced by human activities over their lifetimes[30]. However, with the increasing prominence of global climate change in the world environmental agenda, the Carbon Footprint is also considered an indicator for evaluating the potential impacts of global warming from a lifecycle perspective[31]. Hence, the present Carbon Footprint is a hybrid concept, drawing its nomenclature from the "Ecological Footprint", while functionally operating as a metric for evaluating global warming. Some scholars have even labeled it as "carbon weight" to prevent ambiguity. The unit of measurement is typically expressed in kilograms or tons[32].

In the academic community, there is no unified consensus on the concept of carbon footprint. In most cases, scholars regard "carbon footprint" as carbon dioxide emissions or greenhouse gas emissions expressed in terms of carbon dioxide equivalent (CO_2-e). However, different scholars have different views on the system boundaries and types of greenhouse gases[33]. Wiedmann and Minx[34] believe that the carbon footprint should include both the total amount of CO_2 emissions directly and indirectly caused, as well as the total amount of CO_2 accumulated by products and services over their lifecycle. On the contrary, Peters argues that the carbon footprint should not only encompass carbon, but also account for additional factors that influence climate change. These factors include NO, SO_2, black carbon, land use change, and surface albedo. Peters proposes a comprehensive definition of the carbon footprint as the aggregation of all pertinent emission sources, sinks, and storage related to consumption and production within a specific spatio-temporal system boundary[35]. Additionally, consulting firms, companies, non-governmental organizations, and governments have proposed definitions of carbon footprint according to their own needs. As an illustration, the Carbon Trust in the UK delineates the term "carbon footprint" as the greenhouse gas emissions released across the complete lifecycle of a product, starting from raw material production to product disposal (excluding emissions during use). The Carbon Trust asserts that the "carbon footprint" ought to solely encompass emissions directly associated with products' inputs, outputs, and unit processes. Conversely, certain indirect emissions, like those stemming from workers commuting to factories, should not be factored into the calculation. In terms of research scale, carbon footprint studies cover different scales including individual, product, household, organizational[36,37], city, and national levels[38,39].

According to Tukker *et al.*, the assessment of emissions from an economic entity, such as a country or a household, is driven by the principle of responsibility, which assigns emissions to that specific entity[40]. Within the literature, the consumer responsibility principle is commonly employed to allocate household emissions, specifically attributing emissions to consumers engaged in the supply chain of goods that generate greenhouse gas emissions[41]. This approach of assigning greenhouse gas emissions to households contributes to the establishment of their respective carbon footprints.

Methods of measuring household carbon footprint

The sources of households' carbon footprint fall into two main categories: Firstly, the carbon footprint generated by the consumption behaviors of households, such as household energy consumption from coal, automobile-related energy consumption for transportation, and electricity usage; Secondly, the indirect carbon footprint resulting from household consumption. For instance, although households do not directly generate carbon footprint when consuming bread, the production process indirectly uses coal, electricity, and other energy sources, leading to carbon emissions. Hidden carbon emissions represent the predominant contributor to the carbon footprint within households' consumption processes. Presently, approaches for quantifying households' carbon footprint primarily entail input-output analysis, the carbon emission coefficient method, and life cycle assessment.

Input-output analysis (I-O analysis) is a top-down carbon footprint calculation model based on input-output analysis, initially proposed by American economist W. Leontief. This approach clarifies the connections between inputs, intermediate processes, and outputs, revealing the origins, endpoints, and interconnections of various economic activities. Given the escalating environmental concerns, several scholars have utilized input-output analysis for carbon footprint investigations. The application of carbon footprint analysis based on input-output models has been widespread across numerous cities worldwide[42]. Multiple studies have substantiated the notable benefits of employing input-output analysis to investigate the carbon footprint of household consumption, spanning macro and regional scales. Notably, research conducted by scholars focusing on regions such as Brazil, the Philippines, and northern Europe's Norway has demonstrated that indirect carbon emissions stemming from household consumption represent a substantial portion of the overall carbon emissions[43-45]. Others[46] conducted further research based on input-output models, revealing that over 30% of the UK's carbon footprint originates from overseas. Some researchers[47] studied high-income and low-income families, finding that high-income households have a relatively larger implicit carbon footprint. Certain surveys employed input-output models to compute the implicit carbon footprint of eight sectors in both China and the United States, conducting quantitative analyses[48].

The MRIO model is an effective extension of input-output models, which has significant implications for studying the transfer of carbon emissions. Some findings[49] emphasized that MRIO is a crucial tool for analyzing carbon transfer between regions, effectively avoiding duplicate calculations of carbon emissions between regions. Some investigators[49] compared carbon footprint analyses using input-output tables compiled from the World Input-Output Database and Belgian national agency data, finding higher data accuracy from the Belgian government agencies. Some others[50] suggested that creating a multi-scale MRIO model is the optimal solution for establishing a comprehensive carbon accounting framework for Australian cities.

The IPCC method, known as the Carbon Emission Coefficient method, was established by the United Nations Intergovernmental Panel on Climate Change and is a universally used approach for calculating direct carbon footprints[51]. Due to technological and geographical differences among countries, significant variations exist in carbon emission coefficients. Therefore, in situations where relevant data are incomplete, default emission coefficients provided by the IPCC can be directly employed. In the application of this method, Chinese researchers[52] measured the direct energy consumption carbon emissions of household sectors at the provincial level in China. The IPCC method provides significant convenience in studying the direct carbon emissions of urban and rural households. Based on the latest IPCC report, one study[53] conducted a critical analysis of carbon emission reduction measures. They also analyzed the consumption of enterprise carbon reduction costs based on different proportions of energy consumption costs.

Life Cycle Assessment (LCA) serves as a method to analyze the environmental impacts of a product across its life stages, encompassing production, use, disposal, and recycling. It addresses critical aspects such as energy consumption, resource depletion, and pollutant emissions. Typically, this method entails four primary steps: defining the goal and scope, conducting inventory analysis, performing impact assessment, and interpreting the results[54]. When conducting a life cycle assessment for carbon footprint, it is essential to consider uncertainties in both methods and data. Firstly, selecting appropriate accounting methods, including choices in modeling, treatment of capital goods, and handling of land use changes, can significantly impact the final results. Secondly, ensuring data quality meets the standards of ISO14044[54] and PAS2050[55], including accuracy, representativeness, consistency, reproducibility, data sources, and information uncertainty, is crucial.

The Consumer Lifestyle Approach (CLA) was introduced by Bin and Dowlatabadi[56]. In CLA, consumers are individuals who purchase and use products and services for personal or household consumption. Lifestyle is a way of life that influences and is reflected in an individual's consumption behavior. CLA recognizes that understanding consumers involves the consideration of various interacting factors and provides a comprehensive framework for assessment, including external environmental variables, individual determinants, household characteristics, and consumer choices and the resulting consequences. Additionally, CLA can be utilized to quantify the complete carbon emissions of households, including both direct and indirect emissions[57].

Comparison of advantages and disadvantages of different measurement methods

Input-output analysis allows for the establishment of comprehensive and robust carbon footprints by considering all higher-level impacts and considering the entire economic system as the boundary. This method relies on input-output tables and functions as an economic model. However, achieving this comprehensiveness comes at the expense of sacrificing intricate details. The analysis of microsystems, such as products or processes, is constrained by the assumption of homogeneity in prices, outputs, and carbon emissions at the sector level. Although conducting a more in-depth analysis of individual sectors could bring them closer to microsystems, this potential is generally restricted, particularly on a broader scale. However, input-output-based methods offer a notable advantage: significantly reducing the required time and human resources once the model is established.

The advantage of the IPCC inventory method lies in its comprehensive examination of greenhouse gas emissions resulting from the combustion of different fossil fuels. This method offers convenient data acquisition and relatively straightforward calculation processes, making it suitable for assessing energy carbon footprints at various scales. However, its drawback is its inability to cover implicit indirect carbon emissions. At the meso to micro level, this method typically requires correction through process analysis integration. Additionally, regional variations in production technology levels and energy quality pose challenges in selecting regional emission factors. For instance, China largely uses low-quality coal, resulting in actual emission factors lower than the IPCC default values. As a result, the IPCC inventory method has calculated China's energy and cement carbon footprints to be approximately 15% higher over the past decade[58].

Life cycle assessment (LCA) is a bottom-up method for calculating carbon footprints, with analysis results tailored for micro-level systems, making it suitable for carbon footprint accounting. Scholars have already used this method to assess items such as healthcare equipment, forklifts, water production, small communities, small economies, and bioenergy. Additionally, international standardization organizations such as the International Organization for Standardization (ISO), the British Standards Institution (BSI), and the World Resources Institute (WRI) have already established or are in the process of establishing standards for organization and product carbon footprint accounting, aiming to standardize and promote the application of carbon footprint accounting in enterprises. However, the LCA method faces boundary issues because it considers only direct and a few indirect impacts, potentially leading to truncation errors in the results. Additionally, obtaining detailed inventory data requires a significant investment of human and material resources.

ANALYSIS OF FACTORS INFLUENCING HOUSEHOLD CARBON FOOTPRINT

Economic and social factors

In examining the factors influencing household energy consumption and carbon emissions, economic and social factors emerge as pivotal considerations. These factors exert influence on households through varied pathways and mechanisms, consequently impacting their energy consumption and carbon emission levels. Primarily, economic factors such as income level play a significant role in shaping household energy consumption and carbon emissions. Elevated income levels typically translate to increased consumption capacity for households, enabling them to procure more energy-intensive products and services, thus elevating energy use and carbon emissions. Gao *et al.* elucidate that income growth is among the three primary factors exacerbating carbon inequality, thereby highlighting the intrinsic connection between household income and its carbon emissions[59]. Similarly, Lv *et al.*, through an analysis of the carbon footprints of urban and rural residents in China, ascertain that income level stands out as a key determinant influencing household carbon footprints[60].

Apart from direct economic factors, the education level also exerts a significant impact on household energy consumption and carbon emissions. Education can indirectly influence household energy consumption patterns and carbon emission levels by shaping individuals' environmental awareness, values, and consumption choices. Lv *et al.* demonstrated that households with higher levels of education tend to exhibit greater environmental consciousness and a preference for low-carbon products and services, consequently leading to a reduction in carbon emissions[60]. Concerning social factors, household size and age structure also emerge as pivotal influence factors of household energy consumption and carbon emissions. Zhang *et al.*'s study identified household size as one of the foremost determinants impacting household consumption patterns and carbon footprints[61]. A smaller household size may imply higher per capita energy consumption, particularly in housing and transportation. Furthermore, population aging exerts an impact on household energy consumption and carbon emissions, attributable to variations in consumption patterns and carbon emissions across households of different ages. An *et al.* underscore the significance of household characteristics in shaping household energy consumption and carbon emissions[62]. Through the development of a data-driven model, they evaluated the carbon footprint of Chinese households and identified household size as a pivotal characteristic influencing the carbon footprint. This reaffirms the substantial influence of household characteristics on household energy consumption and carbon emissions.

Consumption behavior and lifestyle

Food consumption significantly contributes to a household's carbon footprint. Yu *et al.*, in a comparative analysis of household carbon footprints in China and Japan, highlighted that consumption expenditure is the primary driver of household carbon footprints in China[26]. Their study indicated that consumption patterns directly affect household carbon emissions, and they found that the carbon footprint from food decreases with economic development, while the housing-related carbon footprint increases. Liu *et al.* emphasized that food consumption plays a pivotal role in influencing household carbon footprints, as evidenced by their examination of households across different age groups in China[63]. This observation was further supported by Kanemoto *et al.* in their research in Japan. They discovered that specific food categories, such as vegetables, fish, sweets, alcoholic beverages, and dining out, were crucial in differentiating between high- and low-carbon households based on their carbon footprints[64].

Furthermore, consumption behaviors and lifestyles related to housing, transportation, and energy have a significant impact on household carbon footprints. A study conducted by Zen *et al.* in Malaysia revealed a strong association between housing type, daily household activities, and carbon footprints, with greater carbon footprints in urban areas compared to rural areas[65]. An *et al.* constructed a data-driven model to assess household carbon footprints in China, and it is expected that carbon footprints of housing will increase with economic development[62]. In their research, Yu *et al.* identified transportation and communication as potential areas for reducing household carbon footprints, emphasizing the potential of these consumption areas in mitigating carbon footprints[26]. In a study conducted in the Philippines by Serino[66], energy-intensive consumption (such as fuel, lighting, and transportation) was found to primarily drive inequality in household carbon footprints, indicating the significance of environmental awareness and behavior in reducing carbon footprints.

Evolutionary trends in household carbon footprints

The influence of various factors on the household carbon footprint changes as the economy develops and the demographic structure shifts. With increasing income levels of individuals, there is a potential rise in demand for energy-intensive lifestyles and consumer goods, resulting in a potential increase in demand for energy-intensive lifestyles and consumer goods[60]. For instance, the addition of household appliances and the requirement for larger housing spaces may contribute to higher household energy consumption and carbon emissions. Simultaneously, economic growth is often accompanied by technological advancements and innovations, which can improve the efficiency of energy utilization and decrease the carbon emission intensity per unit of energy. Appliances with higher energy efficiency and building materials that are environmentally friendly have the potential to lower energy consumption and carbon footprints[59]. Regarding demographic changes, population aging can result in smaller households, thus reducing the per capita efficiency of shared resources and resulting in higher energy consumption and carbon emissions per capita[61]. Furthermore, diverse age groups may exhibit distinct consumption habits and lifestyles, potentially impacting household carbon footprints. Simultaneously, elevated levels of education can enhance awareness of environmental concerns and encourage the adoption of environmentally friendly consumption choices and behaviors, thus potentially reducing household carbon footprints[60].

Due to urbanization, there is likely to be an increased reliance on public transport and denser settlement patterns, thus contributing to carbon emissions reduction. However, urbanization can also result in an increased demand for private vehicles and lifestyles characterized by high energy consumption, thereby increasing carbon emissions[65]. Economic growth can, in turn, affect the distribution of income, which, in turn, affects the consumptive capacity and carbon emissions across households with varying income levels. Households with higher incomes tend to exhibit higher energy consumption and carbon footprints, while those with lower incomes are likely to prefer products and services with low carbon footprints[67].

METHODS AND TOOLS FOR ASSESSING HOUSEHOLD CARBON FOOTPRINT

Carbon footprint assessment models and tools

The cornerstone of carbon footprint accounting is rooted in Life Cycle Assessment (LCA). Serving as an evaluation instrument, LCA is predominantly employed to evaluate and track the complete lifecycle of products or services, including energy consumption and environmental impacts from inception to disposal. Lifecycle impact assessment methods are categorized into two types based on the differences in evaluation purposes: midpoint and endpoint methods. The midpoint method, also known as the problem-oriented approach, focuses on the potential impacts of product lifecycle emissions on the environment itself. Its environmental impact mechanisms mainly involve the migration and transformation patterns of substances emitted into media such as air, water, and soil in the environment. This calculation process is characterized by low uncertainty and high scientific validity. Major midpoint methods include EDIP, CML2001[68], EPSI[69], LUCASH[70], TRACI[71], *etc*.

In contrast, endpoint methods prioritize damage assessment, focusing more on the comprehensive environmental damage experienced by receptors (such as human health, ecosystems, resources, *etc*.)

exposed to emitted substances. Because of the relatively limited research duration associated with this approach and its engagement in interdisciplinary fields such as environmental science, environmental meteorology, toxicology, and epidemiology, the uncertainty in assessment outcomes is slightly higher compared to the midpoint method. However, this method is indicative of the trend in the future development of impact assessment methods. Major endpoint methods currently include Eco-indicator[68], IMPACT2002[72], ReCiPe[73], *etc*. Among them, EDIP, CMI (midpoint method) and Eco-indicator99, ReCiPe (endpoint method) are more widely used.

Micro-level carbon footprint assessment methodology

The household carbon footprint refers to the direct or indirect emissions of carbon dioxide and other greenhouse gases caused by household activities[31]. Typically, assessing the carbon footprint at the individual or household level requires obtaining raw data through questionnaire surveys. Researchers must clarify the survey scope: individual or household level. Subsequently, questionnaire design is conducted based on theoretical frameworks and practical needs.

Specifically, different consumption behaviors and socioeconomic status of households can be assessed by selecting the following indicators: firstly, housing type and housing area to determine housing characteristics; secondly, consumption quantities of grains, meat, fruits, and vegetables to measure food consumption behavior; next, consumption quantities of tobacco, alcohol, clothing, shoes, plastic bags, and laundry detergent to evaluate daily necessities consumption behavior; then, daily commuting distance, commuting transportation mode, monthly travel frequency, family travel distance, and travel mode to analyze transportation consumption behavior; concurrently, household electricity consumption and natural gas consumption to measure direct energy consumption behavior; additionally, bathing frequency, washing machine type, water consumption quantity, and water usage habits to observe water resource consumption behavior; consideration of waste disposal frequency to assess waste consumption behavior; finally, personal education level, occupation, average monthly income, and household population to reflect the socioeconomic status of the household.

Using the IPCC carbon emission coefficient method, the carbon footprint emissions of households are assessed, covering aspects including food, tobacco and alcohol, daily necessities, transportation, household water consumption, direct energy consumption, and direct waste generation. Based on the formulas and carbon emission coefficients provided by the IPCC Fifth Assessment Report, multiplying the household activity data obtained from surveys by the corresponding emission coefficients enables the calculation of the carbon footprint of all sampled households.

Macro-level carbon footprint assessment methodology

The carbon footprint consists of two components: direct carbon footprint and indirect carbon footprint. At the macro level, the direct carbon footprint includes emissions from energy consumption, transportation, and fossil fuel combustion, as well as other sources. In contrast, the indirect carbon footprint pertains to carbon emissions generated throughout the production, manufacturing, and eventual degradation processes of products and services.

The direct carbon footprint of households encompasses carbon emissions from the direct utilization of fossil energy in daily activities, including cooking, heating, and operating vehicles fueled by coal, coke, natural gas, gasoline, diesel, and other energy sources. Notably, electricity and heat represent the primary forms of energy consumed by households for tasks such as powering household appliances and lighting. However, there exists academic debate regarding the classification of carbon emissions associated with electricity and heat consumption[56]. Some scholars contend that since households directly use electricity and heat, the emissions stemming from their consumption should be classified as direct carbon emissions. Conversely, other scholars argue that electricity and heat are products derived from the combustion of fossil fuels within the "electricity and heat production and supply industry". As households procure electricity and heat to fulfill their daily requirements, the carbon emissions linked to their electricity and heat consumption are deemed indirect carbon emissions[74].

According to the IPCC's methodology for computing carbon emissions related to energy consumption, the formula for estimating the direct carbon emissions of households is outlined as follows:

$$CD = \sum_i M_i \times NCV_i \times CC_i \times O_i \times \frac{44}{12}$$

Where CD symbolizes the aggregate direct carbon footprint of households, and the subscript i signifies the category of fossil fuel. Various fossil fuel categories, reflecting households' energy consumption habits, encompass raw coal, processed coal, formed coal, coke, coke oven gas, alternative gases, gasoline, kerosene, diesel, liquefied petroleum gas, and natural gas. M_i represents the direct utilization of the i-th fossil fuel type by households. NCV_i denotes the net calorific value, which signifies the amount of heat produced per unit of fossil fuel i. CC_i represents the carbon content, representing the carbon emissions per unit of net calorific value of fossil fuel i. O_i represents the oxidation rate, indicating the proportion of carbon in fossil fuel i that converts to carbon dioxide. Additionally, the conversion factor from carbon to carbon dioxide is 44/12.

In determining the direct carbon footprint of households, two key datasets are essential: (1) household energy consumption; and (2) carbon emission coefficients for various energy sources. Information regarding household energy usage is sourced from the "China Energy Statistical Yearbook", whereas carbon emission coefficients are derived from recommendations by Liu *et al*., established through empirical measurements aligning with the characteristics of energy sources in China[58].

The indirect carbon footprint of households refers to the hidden carbon emissions embedded in the products and services they purchase, including food, clothing, healthcare, transportation, communication, education, entertainment, and other daily consumption activities. The method for calculating the indirect carbon footprint of households using input-output analysis is as follows:

$$CI = F \times (I-A)^{-1} \times Y$$

Where CI represents the vector of households' indirect carbon footprint, where each element CI_j signifies the indirect carbon footprint of industry sector j. F denotes the vector of direct carbon emission intensity, where each element F_j represents the direct carbon emission intensity of industry sector j. This intensity reflects the carbon emissions per unit of total output, calculated as the total carbon emissions of industry sector j divided by the total output. I represents the identity matrix, while A signifies the matrix of direct consumption coefficients. The matrix (I-A) corresponds to the total requirement coefficients, known as the Leontief inverse matrix. Y symbolizes the consumption matrix of households, structured as a diagonal matrix. In this matrix, the diagonal elements represent the consumption of households in industry sector j.

The main data required for calculating the indirect carbon footprint of households include: (1) China's input-output table; (2) China's carbon emission data; and (3) households' consumption expenditure data.

The China's input-output table is sourced from the National Bureau of Statistics and is used to construct input-output models to reveal the interrelationships among economic activities. Carbon emission data are obtained from the China Emission Accounts and Datasets (CEADS), which publishes the national carbon emission inventory, used to determine the carbon emission levels of various industrial sectors. Households' consumption expenditure data are sourced from the "China Urban (Town) Life and Price Yearbook", used to determine the consumption expenditures of households in various industrial sectors.

CHALLENGES AND PROSPECTS OF HOUSEHOLD CARBON FOOTPRINT ASSESSMENT

Data collection and quality assurance issues

Household carbon footprint assessment presents several challenges related to data collection and quality assurance, significantly impacting the accuracy and reliability of the results. Firstly, ensuring the reliability of data sources becomes paramount. The assessment necessitates detailed consumption and energy use data collection at the household level, often entailing privacy and sensitivity concerns that could impede data accessibility or introduce bias[61]. Additionally, assessing household carbon footprints relies on comprehensive data concerning household consumption, including goods and services purchases. Insufficient data may lead to inaccurate assessment results. Secondly, ensuring data consistency and standardization poses another significant challenge for carbon footprint assessment. Diverse data sources may employ distinct measurement units, classification standards, and collection methods, impeding effective data comparison and analysis. For instance, variations in household consumption patterns across regions and cultures mandate consistent classification standards and measurement units to ensure data comparability[26]. The absence of uniform standards and methods for assessing household carbon footprints complicates result comparison and synthesis across studies.

In addition to data reliability and consistency, the timeliness of data has emerged as a critical issue. Particularly in a dynamic economic and social environment, outdated data may not precisely depict the current situation. Household consumption patterns and preferences evolve over time, necessitating regular data updates to reflect the latest consumption trends[60]. Furthermore, technological advancements in products and services used by households can impact their carbon emission efficiency, requiring prompt integration into assessment models. The assessment of household carbon footprints faces challenges related to data collection and quality assurance, necessitating a blend of data reliability, consistency, timeliness, and updates. This process often demands substantial time and resources, particularly for small organizations or households with limited resources[62]. Implementing advanced data collection technologies, such as mobile applications, online surveys, and automated systems, becomes imperative to enhance the efficiency and accuracy of data collection.

Evaluators must implement effective measures to confront these challenges and ensure the precision and credibility of evaluation results, thereby bolstering the formulation of impactful low-carbon policies and measures. By continually enhancing data collection and quality assurance methods, a deeper understanding and better management of household carbon footprints can be achieved, aligning with the objectives of sustainable development and climate change mitigation.

Challenges in model establishment and parameter selection

The development of carbon footprint assessment models and the selection of parameters represent a nuanced and pivotal endeavor, fraught with several intricate challenges. Firstly, the establishment of assessment models necessitates meticulous consideration of the reliability and comprehensiveness of data. Data integrity directly underpins the fidelity and validity of the model outcomes. Incomplete or outdated datasets pertaining to households' consumption patterns and energy utilization may engender biases within the model. Hence, ensuring the fidelity of selected data to authentically portray consumption behaviors and energy utilization is imperative during model inception. This may entail employing cross-validation techniques utilizing diverse data sources to ensure data exhaustiveness and precision.

Secondly, parameterization mandates adherence to principles of data consistency and standardization. Variegated parameters and measurement units across disparate data sources may engender impediments to seamless model comparison and analysis. To foster model efficacy and comparability, data harmonization efforts are imperative to ensure parameter uniformity. This may necessitate the formulation of standardized parameter regimes and measurement metrics to facilitate cogent comparisons and analyses across divergent model frameworks. Furthermore, parameter selection requires a nuanced understanding of regional and demographic differences to emphasize model applicability and generalizability.

Beyond data fidelity and parameter consistency, temporal fidelity of the model assumes salience. Particularly in rapidly evolving socioeconomic milieus, models mandate timely updates to reflect emergent developments. This entails periodic model scrutiny and recalibration to encapsulate shifting consumption behaviors and energy utilization paradigms. At the same time, rapid acquisition and integration of current data are necessary to maintain model accuracy and reliability. Using advanced technologies like data mining and artificial intelligence can speed up model updates and improve efficiency.

In summary, developing carbon footprint assessment models and selecting parameters is fraught with multifaceted challenges, requiring careful consideration of data integrity, consistency, and temporal accuracy. By adopting holistic methodologies and advanced technological interventions, these challenges can be addressed, improving the accuracy and credibility of the model and providing empirical support for promoting low-carbon initiatives.

Prospects and future development trends in research directions

The future prospects and development directions of household carbon footprint assessment involve several key areas, necessitating a comprehensive consideration of challenges and improvement strategies such as data quality assurance, standardization, dynamic modeling, and technological integration. Firstly, strengthening data quality assurance is crucial. Future research should focus on establishing robust data collection mechanisms to ensure data reliability, completeness, and timeliness. This may require establishing close collaborations with relevant institutions to jointly develop and enforce stringent data-sharing frameworks, with periodic audits to ensure data quality. Additionally, promoting standardization and consistency is also a critical focus of future research. Standardizing measurement units, classification standards, and data collection methods can help eliminate differences among various data sources, facilitating more effective comparisons and analyses. Future research should aim to formulate unified data collection and reporting standards and guidelines to advance standardization efforts.

Furthermore, future research should explore dynamic modeling frameworks. Traditional static modeling approaches may not timely reflect changes in the rapidly evolving economic and social environments. Therefore, future research can explore the development of dynamic modeling frameworks capable of adapting to evolving circumstances. This may involve integrating real-time data monitoring and analysis capabilities into carbon footprint assessment models to enable continuous updates and adjustments based on evolving conditions. Additionally, technological integration is another focal point of future research. Leveraging advanced technologies such as artificial intelligence and big data analytics can significantly enhance the efficiency and accuracy of data processing and analysis. Future research should explore integrating these technologies into carbon footprint assessment models to achieve automated data processing and improved predictive capabilities. By comprehensively addressing these challenges and development directions, future household carbon footprint assessment research can better support and guide the construction of low-carbon societies.

DISCUSSION

Household carbon footprint research provides crucial insights into individuals' and households' contributions to climate change. Analyzing household carbon footprints helps identify major sources of carbon emissions, assess the environmental impacts of various consumption behaviors, and provide recommendations for developing emission reduction policies and individual carbon reduction actions.

In the field of household carbon footprint research, interdisciplinary research methods are recommended. This approach integrates expertise from various disciplines, including environmental science, sociology, economics, and policy studies, to deeply analyze the mechanisms and influencing factors behind carbon footprint formation. An interdisciplinary perspective allows us to comprehensively understand the impact of residential lifestyles, consumption habits, and social structures on carbon emissions. This not only helps reveal the complex relationships behind carbon footprints but also provides more comprehensive and in-depth theoretical support for formulating targeted carbon reduction policies.

Secondly, the application of big data and artificial intelligence (AI) technologies in carbon footprint research should be promoted. By analyzing vast amounts of carbon footprint data using big data and combining AI models and algorithms, we can more accurately assess households' carbon emissions and predict future carbon footprint change trends. This data-driven approach not only provides a scientific basis for decision-makers but also discovers potential patterns and influencing factors of carbon emissions, offering innovative tools and methods for formulating more effective carbon reduction strategies. The introduction of this cutting-edge technology will make carbon footprint research more precise, real-time, and deepen academic understanding in this field.

Furthermore, conducting long-term longitudinal studies to explore the evolution of household carbon footprints and the continuous changes in influencing factors is suggested. Through cross-year data collection and analysis, we can better understand the relationship between carbon emissions and economic development, social changes, and policy measures. Such long-term research will help identify trends in carbon footprint changes, recognize key factors influencing carbon emissions, and evaluate the long-term effects of different policies and measures. Additionally, it can reveal potential patterns of change and warning signals, providing important references and predictions for future carbon reduction decisions. The continuity and systematic nature of this long-term research will provide a more reliable and comprehensive foundation for academic research and policy-making in the field of carbon footprints.

CONCLUSION

Various methods are employed in measuring carbon footprints, including input-output analysis (IO analysis), the IPCC method (Carbon Emission Coefficient Method), and Life Cycle Assessment (LCA). Each method possesses distinct strengths and weaknesses, rendering them suitable for different scales and depths of analysis. IO analysis offers comprehensiveness but may overlook microsystem details; the IPCC method provides a thorough review of GHG emissions but lacks consideration of indirect carbon emissions; and LCA offers customized microsystem analysis but grapples with boundary issues and resource demands. In carbon footprint accounting, LCA serves as a vital method supporting decision making by evaluating environmental impacts through midpoint and endpoint approaches.

At the individual and household levels, questionnaires and the IPCC method emerge as primary tools, while at the community and city levels, input-output analysis is utilized to compute the indirect carbon footprint. These methodologies not only yield insights into carbon emissions across different scales but also furnish essential data for crafting effective climate change mitigation strategies. Therefore, informed decisions are crucial when selecting a carbon footprint measurement method, contingent upon research objectives and resource availability.

Previous studies have demonstrated the significance of consumption behaviors and lifestyles in influencing household carbon footprints. Modifying consumption habits, opting for eco-friendly products, embracing energy-efficient lifestyles, and enhancing environmental consciousness can effectively mitigate the consumption of energy and resulting carbon emissions in households. These findings from the research offer a crucial foundation for the development of policies and strategies aimed at mitigating household carbon footprints. Additionally, economic development and demographic changes constitute dynamic processes that impact energy consumption and carbon emissions via various pathways. Therefore, understanding these changes and their potential influences on household carbon footprints is crucial for formulating effective mitigation strategies.

While this study aims to provide a comprehensive analysis of household carbon footprints, it is important to acknowledge that the study's depth and breadth may be constrained by limitations in resources and scope and, thus, may not encompass all pertinent details and aspects. The study may have overlooked other potential or emerging carbon footprint measurement methods, and the discussion on the applicability of different methods in varying contexts may be insufficient. Regarding the factors that impact household carbon footprints, there may be an inadequate exploration of the psychological and social motivations underlying consumption behaviors. Furthermore, the analysis of long-term trends in household carbon footprints may lack support from adequate historical data or case studies.

To provide a more comprehensive perspective, future research should encourage interdisciplinary studies that integrate theories and methods from different fields. Diversified research methods, including qualitative research and case studies, are encouraged to enrich the research. Long-term tracking studies should be conducted to observe and analyze the dynamic changes and trends in household carbon footprints.

DECLARATIONS

Authors' contributions

Writing original draft: Zhong Z, Du J
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Availability of data and materials

Confirmation that all data supporting your conclusions is fully presented within the article itself.

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Conflicts of interest
All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

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