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*Original Research*

# Estimation of Carbon Footprint of Honey Production: A Case from China

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## Abstract

The carbon footprint is used to quantify the amount of carbon emitted throughout the production process. It is considered a crucial environmental metric amid global warming concerns, drawing attention from both consumers and producers. Given China's status as the leading producer of honey worldwide, there is a pressing need for an environmental sustainability metric to assess the life cycle carbon emissions associated with beekeeping with a view to sustainable development. This study assesses the carbon footprint of Chinese honey products from the "cradle" to the "gate", revealing that the carbon footprint is 0.81±0.106 $CO_2$eq/kg honey. This value is distributed across various stages of honey production, encompassing hive management, long-distance transport for pollination, honey extraction and processing, as well as the transport of processed honey. It is noteworthy that the calculated carbon emissions associated with these stages are 0.054, 0.339, 0.299, and 0.118 kg $CO_2$eq/kg honey, accounting for 6.84%, 40.29%, 37.93%, and 14.92% of the total carbon emissions in honey production, respectively. This indicates that long-distance transport for pollination and the honey extraction process play a pivotal role in the honey production process, with fossil fuels consumed for long-distance transport and electricity consumed for honey extraction and processing being the primary sources.

**Keywords:** honey production, carbon footprint, sustainability metrics, migratory beekeeping, environmental impact

## Introduction

Human-induced greenhouse gas (GHG) emissions, which poses mounting threats to ecosystems and human well-being, jeopardizing future development. Rising global temperatures lead to multiple climate hazards, such as increased heatwaves, droughts, and floods, contributing to biodiversity loss and exposing millions of people to acute food and water insecurity. Addressing GHG emissions and mitigating climate change is not only an environmental imperative but also a crucial aspect of sustainable economic development [1, 2]. In response to this pressing challenge, the international community has reached consensus on goals to reduce $CO_2$ emissions and promote the development of a low-carbon economy [3]. In 2018, the Intergovernmental Panel on Climate Change (IPCC) set a stricter limit of 1.5ºC of warming and aimed to achieve carbon neutrality by the mid-century. China, as a UN Member State and a permanent member of the United Nations

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Security Council, is actively engaged in global efforts to mitigate climate change [4]. At the 75th session of the United Nations General Assembly in 2020, the Chinese government pledged to strive for a peak in carbon dioxide emissions by 2030 and attain carbon neutrality by 2060. This commitment underscores a dedication to institute practical measures to curtail carbon emissions, which is critical to achieving global climate objectives. Such endeavors are consistent with the collective expectations of the international community and contribute to a more sustainable future.

The agricultural sector constitutes the second-largest source of GHG emissions, accounting for approximately 10-12% of the total GHG emissions. Within China, this sector makes up a substantial 17% of the nation's overall carbon emissions, contrasting sharply with the 7% contribution from agriculture in the United States [5-7]. This stark contrast underscores the urgent necessity for China to bolster its efforts in reducing agricultural emissions and enhancing carbon sequestration in soils. Over recent decades, numerous researchers have endeavored to achieve the ‘dual carbon’ objectives in agriculture, developing a multitude of viable approaches. However, substantial variations in the research results have been observed. Some studies indicate that China’s agricultural carbon emissions, despite annual fluctuations, exhibit an overall downward trend. Other research studies have illustrated that while the intensity of China’s agricultural carbon emissions is on a declining trajectory, the total volume of carbon emissions from the agricultural sector continues to increase steadily [5, 8]. Huang et al. (2022) demonstrated that China’s agricultural carbon emissions are undergoing a developmental cycle characterized by “rapid growth-slow growth-accelerated reduction” [9]. Furthermore, a substantial body of research confirms the presence of spatial spillover effects in agricultural carbon emissions [10, 11]. The considerable levels of GHG emissions associated with agricultural production processes have triggered concerns among producers and consumers about the carbon footprint (CF) of various food products and mitigation strategies [12, 13]. In this context, the calculation of carbon emissions from food products and related research assumes a particularly crucial significance. Through a comprehensive tracking of the CF of agriculture, this study has conducted a thorough and accurate assessment of carbon emissions at various stages of agricultural production, thereby enabling precise analysis of the focal areas of carbon emissions and promoting the practical realization of China’s dual carbon goals.

Honeybees, as a fundamental component of ecosystems, play an essential role in conserving biodiversity, combating climate change, and enhancing both crop yield and quality [14]. Beekeeping refers to the agricultural practice of artificially rearing honeybees for product extraction. Honey emerges as the primary product with a high energy density, which has been identified as a vital food and calorie source for early human societies [15, 16]. Furthermore, honey contributes significantly to contemporary diets, providing essential energy for brain development, offering benefits that include combating obesity and supporting liver function, and featuring properties that are antioxidant, antimicrobial, and anti-neoplastic [17-19]. Beekeeping has been an integral part of China’s agricultural heritage for centuries. China is one of the top producers and exporters of honey. According to the China Statistical Yearbook, honey production reached 472,700 tons in 2021, accounting for over a quarter of global honey production, with an export volume of 146,000 tons [20, 21]. Despite national standards for the quality of honey products (GB 14963-2011), there are inadequacies in environmental legislation concerning pollution regulation and green production standards. The primary form of bee-derived commodity in China is often immature honey, which is subjected to processes such as filtering, dehydrating, eliminating impurities, reducing moisture, and packaging, all of which have implications for carbon emissions [22]. Stationary and migratory beekeeping are the two most dominant production practices in Chinese beekeeping. While migratory and stationary practices typically differ in honey production, distance between apiaries, and frequency of food management and handling [23, 24]. The corresponding processes and inputs required for honey production also vary significantly between the two types of apiaries, as do their associated environmental impacts. Migratory beekeeping, which often involves moving hives from one location to another using vehicles, results in burning fossil fuels, generating direct $CO_2$ emissions. In contrast, stationary beekeeping has a constant location and requires no or very little transportation of this type. Furthermore, the maintenance of the health and vitality of bees during migration can further necessitate additional energy consumption, such as the cooling or heating system to regulate the temperature inside the vehicle. This additional energy consumption also increases carbon emissions [25, 26].

To promote sustainable agricultural practices with reduced carbon emissions, this study adopts honey as the research subject and incorporates the life cycle theory to analyze carbon emissions from honey production and their distribution among different production processes. This study introduces a fresh approach to assessing and managing carbon emissions from the breeding processes of special economic animals. The main contributions of this study are: (1) an initial calculation of the CF associated with honey produced in China; (2) an assessment of the CF resulting from activities including beehive management (BBM), long-distance transport for pollination (TD), honey extraction and processing (E&P), and transport of processed honey (TS); and (3) an inventive review of changes in carbon emissions levels across different provinces throughout the various phases of the honey production life cycle.

This study is organized into six sections, the first of which is an introduction. The second section is a literature review. Section 3 provides a comprehensive description of the research methodology utilized in this study. Section 4 discusses the empirical results obtained during the study. Section 5 provides an in-depth discussion of the findings and implications. The final section concludes the study with recommendations based on the findings and a summary of the study's limitations and potential future research directions.

## Literature Review

Life cycle assessment (LCA) is an evaluation tool for estimating and accounting for the mass and energy input and output flows that would be subsequently translated with characterization factors into environmental impacts throughout its life cycle, i.e., from cradle to grave. Cradle-to-grave generally encompasses the full range of operations, from raw material acquisition to conversion into a finished product, and the subsequent stages of production, processing, transport, consumption and use, and final waste disposal [27]. The three predominant LCA methodologies prevalent in scholarly research are process-based LCA, economic input-output LCA, and hybrid LCA [28]. The ISO standards governing LCA (ISO 2006) describe the principles and framework, including Purpose and Scope, Inventory Analysis, Impact Assessment, and Interpretation [29].

The concept and name of CF originate from the ecological footprint concept originally introduced by William and Mathis and refer to the total amount of $CO_2$ emissions arising either directly or indirectly from a specific activity [19, 30]. The CF, an aspect of LCA, concentrates on measuring and assessing the impact of greenhouse gas emissions, especially carbon dioxide emissions. Its methodologies share a common foundation and standards with LCA. Specifically focused on CF, PAS 2050 and ISO 14067 provide specific requirements and guidelines for calculating and assessing the CF of products [31]. These standards build on the broader LCA framework provided by ISO 14040 and ISO 14044 [32].

In recent years, LCA studies have become increasingly crucial in assessing the sustainability of various industries, including the production of honey (Table 1). This literature review aims to highlight the multifaceted nature of honey production systems and offer comprehensive insights into the environmental impacts of honey production, considering various system boundaries, functional units, and allocation methods. Arzoumanidis et al. (2020) conducted a Cradle-to-Gate LCA framework using SimaPro software to explore environmental hotspots in the life cycle of two types of honey (orange-blossom and cherry-blossom) produced by the same small-sized Italian apicultural company, employing an attributional approach based on ISO 14040 and 14044 standards. Their study focused on hive management and honey extraction, emphasizing the initial stages of honey production [33]. Kendall et al. (2013) provided a process-based LCA within the framework of ISO guidelines, primarily addressing air emissions. Despite the limitations of not fully specifying the system boundaries, the study emphasized economic allocation as a baseline method for coproduct allocation. This research highlighted the importance of transportation in the life cycle of commercial honey production, suggesting that reducing transport distances and adopting more efficient transport modes could significantly mitigate environmental impacts [34]. Mujica et al. (2016) approached the carbon footprint of honey production from a cradle-to-grave perspective, based on ISO 14040. They employed a bottom-up methodological approach, focusing on the individual impacts of different stages during honey production. The findings emphasized the predominant role of the extraction process in greenhouse gas emissions, accounting for over 90% of total emissions in the evaluated scenarios [35]. Pignagnol et al. (2021) conducted an LCA using open LCA software, following ISO 14040 and 14044 standards. This study estimated the Carbon Footprint (CF) of honey produced in different beekeeping systems. It proved notably insightful in revealing the impact of electricity consumption in the honey extraction phase, thereby making a significant contribution to the CF on various beekeeping farms [36]. Pignagnoli et al. (2023) extended the system boundary from cradle to farm gate, adopting an attributional approach and focusing on the climate change impact category. The results identified transport and supplemental feeding as significant contributors to overall greenhouse gas emissions in beekeeping, reinforcing the environmental significance of these aspects in honey production. A comparative analysis of Pignagnoli's study, which focuses specifically on transport and supplemental feeding, delves into the extended supply chain [26]. In contrast, Moreira et al. (2019) employed SimaPro software through the ReCiPe methodology guidelines and underscored the significant contributions of hive management and final packaging to greenhouse gas emissions [37]. Vásquez-Ibarra et al. (2022) used openLCA software and the ILCD version 1.0.8 2016 midpoint method for their LCA, evaluating a wide range of environmental impact categories [38]. Through a cradle-to-gate assessment, the research findings indicated that feeding and transport emerged as the primary environmental hotspots in honey production, aligning with the outcomes observed in Moreira's study. This convergence in findings between Vásquez-Ibarra et al. and Moreira et al. further reinforces the significance of feeding and transport in beekeeping practices. The coherence among these above studies collectively underscores the significance of adopting sustainable practices in honey production. While methodologies and scopes vary, the shared focus on carbon footprints and greenhouse gas emissions reflects a growing awareness of ecological sustainability challenges within the apiculture industry. Addressing these identified hotspots presents a strategic opportunity for beekeepers

Table 1. Comparison of Studies on Honey Carbon Footprint.

| Study | System Boundaries | Software | LCA Perspective | Methods Used | Production Stages |
|---|---|---|---|---|---|
| Arzoumanidis et al. (2020) | Cradle-to-gate | SimaPro | Attributional | ISO 14040 and 14044 | Hive management to honey extraction |
| Kendall et al. (2013) | - | - | Process-based | ISO | Raw honey production and processing |
| Mujica et al. 2016 | Cradle-to-grave | - | Bottom-up, based on process analysis | ISO 14040 | Hive management, extraction process, freight to export port |
| Pignagnol et al. (2021) | - | openLCA | - | ISO 14040 and 14044 | - |
| Pignagnoli et al. (2023) | Cradle-to-gate | - | Attributional | ISO 14040 and 14044 | Hive management to honey extraction |
| Moreira et al. (2019) | Cradle-to-gate | SimaPro | - | ISO | Hive management, honey extraction, final packaging |
| Vásquez-Ibarra et al. (2022) | Cradle-to-gate | OpenLCA | - | - | Feeding, medication, transport, extraction, consumption of disposable inputs |

and industry stakeholders to implement more sustainable practices, aligning with the broader goal of reducing the environmental impacts of food production.

The objective of this research is to evaluate the CF of honey products in China based on the ISO standard [32]. This paper examines the CF of the four key stages of honey production, including beehive management, long-distance pollination, honey extraction and processing, and transportation of processed honey. By assessing the unique characteristics of migratory beekeeping and the preparation of unripe honey, our study has developed a fresh and enlightening Chinese perspective on exploring the potential of a unique agricultural economy to reduce the CF associated with honey products. Further, this research draws inspiration from the work of María Mujica et al. (2016) and defines GHGs as carbon emissions, given that carbon emissions make up 98% of GHG emissions. Through these scenarios, this study addresses the following research question: What is the CF associated with the production of one kilogram of honey products in China? How much carbon dioxide is released during different production stages? By conducting measurements, it can pinpoint the origins of carbon emissions, facilitate the identification of areas for improvement in processes and management, and provide specific recommendations to reduce carbon emissions in the beekeeping industry.

## Materials and Methods

### System Boundaries and Functional Units

Fig. 1 illustrates the system boundaries of China's honey production under study. The production process is divided into four subsystems, including beehive construction, beehive management, production and processing, and transportation. The dashed line defines

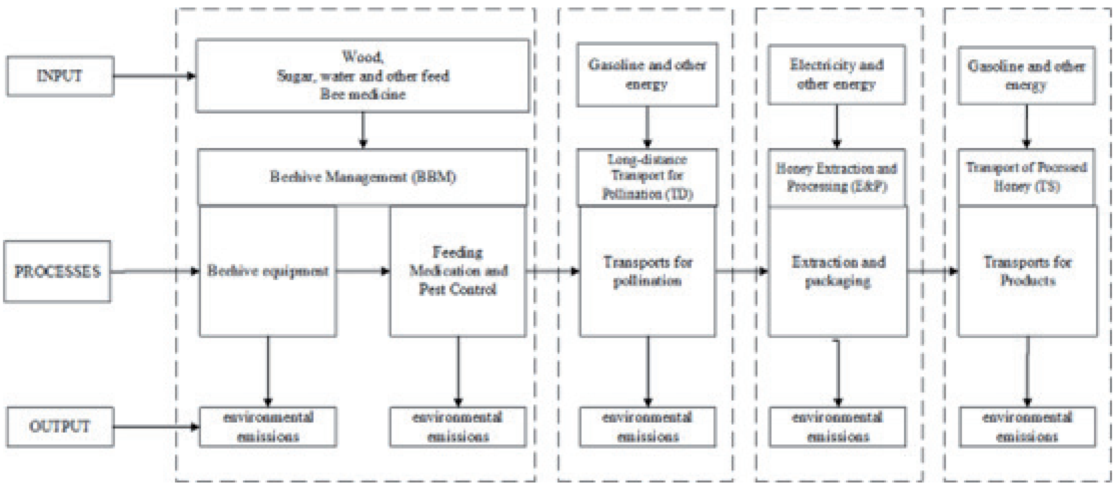


Fig. 1. Flow diagram of the boundary for the LCA of the beekeeping chain in China.

the system boundary for assessing the CF of honey products in China. In this context, inputs include the various elements of production, such as bee medicine, sugar, electricity, fossil energy, etc., while outputs are carbon emissions produced during the production process. To estimate the CF of honey products, this study calculated the equivalent amount of carbon dioxide generated at each stage within these subsystems. The system boundary is specified in predefined conditions for the study, and the 'cradle-to-gate' approach is chosen in line with the literature related to Tricase et al. (2018).

The CF of honey products includes both direct and indirect emissions. The productive activities covered are BBM, TD, EP, and TS.

This study utilizes direct research engagement with beekeepers to obtain beekeeping information, as illustrated in Fig. 1. The BBM phase, which refers to beehive management, includes bee construction, feeding, medication, and pest control. Our investigation into beehive construction, which involves crafting structures for housing bee colonies for honey production and pollination, revealed that the most used materials are natural woods, alongside plastic and various synthetic materials. Apart from beehive materials, a significant focus is placed on beekeepers' spending on essential items such as feed, bee medicines, insecticides, and related materials. The significance of the feeding process is paramount due to the necessity of supplementary feeding in scenarios where natural sources of bee food, such as nectar and pollen, are scarce or absent, or honey reserves within hives are found to be insufficient [39]. Considering the diversity in feed preparation methods, this study adhered to a standardized formula: a 1:1 weight ratio of sugar to water, following the guidelines from the Cornell University Master Beekeeper Program in 2006. It is also imperative to stress that the preparation process for bee feeding requires the application of heat, citing the consumption of both water and electricity as vital considerations that should be factored into a comprehensive assessment. Bees are susceptible to a variety of disease threats, including viruses, parasites, bacteria, and fungi [40]. In this study, medication is essential for bee feeding and the disinfection of related instruments. However, overuse of bee medicines can lead to the accumulation of drug residues in honey products, significantly affecting the exportability of honey products. The inclusion of bee medicines in our analytical calculations serves a dual purpose. It not only accounts for the environmental impact of bee medication, but also aims to encourage alternative biofriendly control methods, thereby safeguarding both bee health and the quality of honey products.

The TD phase in beekeeping, which primarily involves relocating honey bees for pollination or honey production, often involves the utilization of vehicles like trucks or vans. Vehicles, powered by the combustion of fossil fuels, release $CO_2$ into the atmosphere. The increase in transport distance correlates with a corresponding rise in fuel consumption, and subsequently, $CO_2$ emissions. It is therefore crucial to adopt eco-conscious practices to mitigate CF during honey bee transport.

The E&P phase entails the extraction and packaging of unripe honey containing a high moisture content through a process line. To carry out the extraction and packaging phases efficiently, machinery is employed. These machines require electricity for various functions, including powering extraction equipment, providing heat for processing, cooling honey, or maintaining optimal lighting conditions within the facility. Electricity generation often relies on the burning of fossil fuels, which release greenhouse gases (GHG) into the atmosphere. Consequently, a considerable amount of energy is consumed during this phase.

The TS phase of honey products can generate GHG emissions through various activities involved in moving the processed honey from the production site to various markets. Honey products are transported via trucks or other vehicles over long distances. These vehicles typically run on fossil fuels like gasoline or diesel, which release carbon dioxide and other GHGs into the atmosphere when burned. Despite the fragmented nature of the honey market, demands are emerging in regions with elevated population densities. To accurately evaluate the CF associated with the transportation stage, the distance from each beekeeper's production location to the nearest first-tier city in China is considered. This method offers a feasible framework for quantifying the environmental impacts of honey product transportation.

## Characteristics of Chinese Beekeeping

This study investigates the honey production of 24 beekeepers engaged in migratory beekeeping. Data for the study were sourced from a statistical survey conducted by the National Bee Industry Technology System Project, the Department of Science and Technology Education, and the Ministry of Agriculture and Rural Affairs.

Table 2 presents the main characteristics of the sample beekeepers. The average age is 50.96 years, indicative of a pronounced aging trend prevalent in China's beekeeping sector. Furthermore, these beekeepers possessed extensive experience, averaging 32.2 years, ranging from a minimum of 10 to a maximum of 50 years, indicating their considerable expertise in beekeeping. In terms of honey production, the average yield per household is 8,655.42 kg, while the average cost of supplemental sugar syrup and bee medication is CNY 18,742.71 and CNY 1,942.5, respectively.

Migratory beekeeping is a practice where beekeepers transport their beehives over long distances to maximize honey production. This practice involves the tactical movement of hives to various locales, determined by the seasonal availability of nectar and pollen sources. Fig. 2 illustrates the transfer routes of beekeepers, and the transfer distances of beekeepers are listed in

Table 2. Production characteristics of beekeepers.

| Variables | Mean | Std. Dev | Min | Max |
|---|---|---|---|---|
| Age | 50.96 | 9.80 | 29.00 | 69.00 |
| Year of beekeeping | 32.21 | 10.48 | 10.00 | 50.00 |
| Number of household beekeepers | 2.08 | 0.58 | 1.00 | 4.00 |
| Annual yield of honey (kg) | 8655.42 | 4628.80 | 3000.00 | 20000.00 |
| Cost of feeding sugar (CNY) | 18742.71 | 9708.87 | 4500.00 | 42000.00 |
| Cost of bee medicine (CNY) | 1942.50 | 1080.68 | 300.00 | 5000.00 |

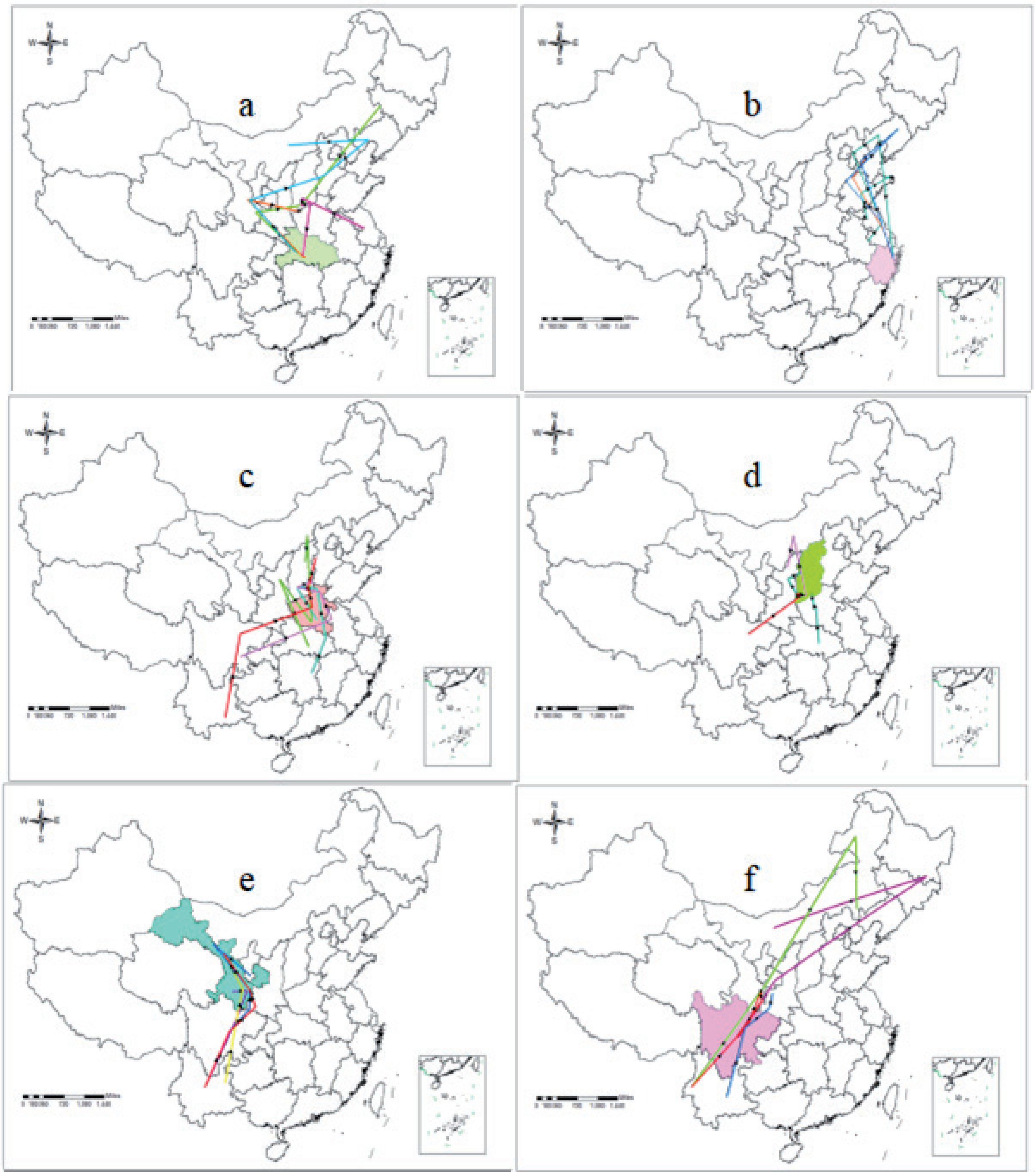


Fig. 2. Beekeeper transport route maps for the Chinese regions of a) Hubei, b) Zhejiang, c) Henan, d) Shanxi, e) Gansu, and f) Sichuan.

Table 3. Distance of transportation for pollination.

| Sample Code | 1103 | 1202 | 1203 | 1303 | 8401 | 8402 | 8411 | 8603 | 4305 | 4808 | 4810 | 4911 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Transport Distance (km) | 991.2 | 3840.1 | 3031.5 | 4000.3 | 2263.6 | 2107.3 | 3167.8 | 4663.5 | 3545.1 | 2130.9 | 2651.1 | 3380.6 |
| Province | Zhejiang | | | | Hubei | | | | Henan | | | |
| Sample Code | 6105 | 6202 | 6417 | 6509 | 11109 | 11112 | 11501 | 11104 | 12202 | 12313 | 12411 | 12108 |
| Transport Distance (km) | 6368.1 | 6292.9 | 3198.6 | 1815.6 | 661.0 | 1496.3 | 961.8 | 1494.8 | 2739.7 | 2782.1 | 2067.4 | 2150.7 |
| Province | Sichuan | | | | Shanxi | | | | Gansu | | | |

Table 4. Main statistical data of the life cycle inventory for producing 1 kg of honey.

| Main inputs | Average | Maximum | Minimum | Stage |
|---|---|---|---|---|
| Woods (kg) | 3.70E-02 | 4.1E-02 | 3.3E-02 | Beehive construction |
| Feeds (kg) | 2.43E-01 | 5.1E-01 | 1.54E-01 | Beehive management |
| Medicines (kg) | 6.41E-04 | 1.65E-04 | 8.6E-02 | |
| Electricity (kWh) | 2.91E-02 | 6.1E-02 | 1.8E-02 | |
| Water (L) | 2.43E-01 | 5.1E-01 | 1.54E-01 | |
| Diesel (kg) | 1.08E-01 | 1.71E-01 | 4.4E-02 | |
| Electricity (kWh) | 4.88E-01 | 6.99E-01 | 2.29E-01 | Extraction and Packaging |
| Diesel (kg) | 3.70E-02 | 6.50E-02 | 1.00E-02 | Transportation of the product to the market |

Table 3. The average distances of Zhejiang, Hubei, Henan, Sichuan, Shanxi, and Gansu are 2965.8 km, 3050.6 km, 2926.9 km, 4418.8 km, 1153.5 km, and 2434.9 km, respectively. It is evident that the average transit distance for beekeepers in Shanxi province is the shortest, whereas those in Sichuan province engage in the longest. There is a direct correlation between bee migration distance and the resultant carbon emission equivalents generated during the migration process.

## Life Cycle Inventory

To guarantee data integrity, six representative provinces (Zhejiang, Shanxi, Henan, Hubei, Gansu, and Sichuan) were selected, with four beekeepers from each province comprising the sample. This research also incorporated the LCIs listed by Leonardo et al. (2023), and the LCIs are shown in Table 4.

## Methods of Calculation

The carbon footprint of honey in this study is calculated in accordance with equation (1), where *CF* is the emission in kg $CO_2$eq, $q_j$ is the amount of input *j,* and $ef_j$ is the carbon emission factor associated with input *j*.

$$CF = \sum q_j \cdot ef_j \tag{1}$$

In instances where direct quantification of certain inputs utilized by beekeepers is unavailable, this study collects relevant input prices. The usage of these inputs is subsequently deduced in accordance with equation (2). In this equation, $c_j$ represents the cost spent by the beekeeper on input *j*, and $p_j$ is the average market price of input *j*.

$$q_j = \frac{c_j}{p_j} \tag{2}$$

## Definition of Functional Unit

In alignment with the IPCC Guidelines, as well as referencing the research by Zhe Li et al., the 100-year global warming potential (GWP) is expressed in carbon dioxide equivalents ($CO_2$eq) in this study. The functional unit of this research is the emission of carbon dioxide equivalents per kilogram of honey produced, denoted as $CO_2$eq/kg honey.

# Results and Discussion

## Results

The carbon emission factors involved in the study are shown in the Appendix, with the results derived from the methodology presented in Section 3. As illustrated in Fig. 3, the calculated CF is 0.81 kg $CO_2$eq/kg honey in China. The predominant source of carbon emissions is the TD stage, which contributes 0.339 kg $CO_2$eq/kg honey, which accounts for 40.3% of the total emissions.

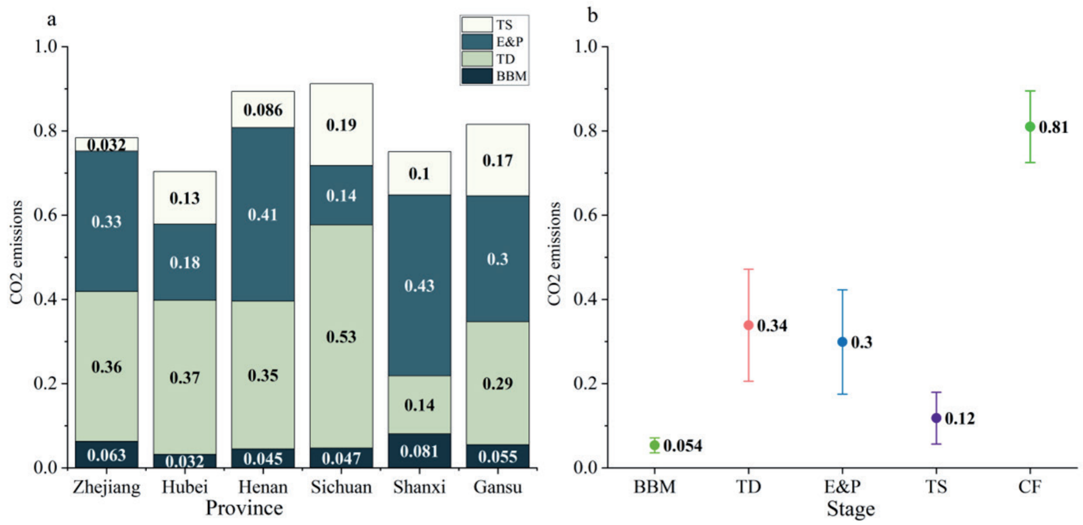


Fig. 3. Carbon emissions and their share in each stage of honey. (BBM, TD, E&P, and TS represent beehive management, long-distance transport for pollination, honey extraction and processing, and transport of processed honey).

The E&P and TS stages generate 0.299 kg $CO_2$eq/kg honey and 0.118 kg $CO_2$eq/kg honey, accounting for 37.93% and 6.85% of the total emissions, respectively.

Significant regional disparities in carbon emissions are observed at various stages of honey production across different provinces (Table 5). During the BBM stage, the average carbon emissions are 0.054 kg $CO_2$eq/kg honey. In the provinces of Zhejiang, Shanxi, and Gansu provinces, emissions surpass the average, with respective emissions of 0.063 kg $CO_2$eq/kg honey, 0.081 kg $CO_2$eq/kg honey, and 0.055 kg $CO_2$eq/kg honey, accounting for 8.05%, 10.77%, and 6.74% of the total emissions in each respective province. In contrast, Hubei, Sichuan, and Henan provinces have below-average emissions of 0.032 kg $CO_2$eq/kg honey, 0.045 kg $CO_2$eq/kg honey, and 0.047 kg $CO_2$eq/kg honey, contributing 4.55%, 5.03%, and 5.15%, respectively.

The TD stage has an average carbon emission of 0.339 kg $CO_2$eq/kg honey. Zhejiang, Hubei, Sichuan, and Henan provinces report above-average emissions of 0.356 kg $CO_2$eq/kg honey, 0.366 kg $CO_2$eq/kg honey, 0.351 kg $CO_2$eq/kg honey, and 0.53 kg $CO_2$eq/kg honey, respectively. These correspond to 45.47%, 51.99%, 39.26%, and 58.11% of the total emissions, respectively. In contrast, carbon emissions in Shanxi and Gansu provinces are below average, at 0.138 kg $CO_2$eq/kg honey and 0.292 kg $CO_2$eq/kg honey, accounting for 18.35% and 35.78%, respectively.

During the E&P stage, the average carbon emission is 0.299 kg $CO_2$eq/kg honey. High carbon emissions are observed in Zhejiang, Henan, and Shanxi provinces, with respective emissions of 0.333 kg $CO_2$eq/kg honey, 0.412 kg $CO_2$eq/kg honey, and 0.429 kg $CO_2$eq/kg honey, contributing 42.53%, 46.09%, and 57.05% to the total emissions within each province. In Sichuan province, carbon emissions are below average, averaging 0.141 kg $CO_2$eq/kg honey, which accounts for 15.46% of the total emissions. Gansu province's emission acts align with the average, accounting for 36.64% of the total carbon emissions.

For the TS stage, the average carbon emission is 0.118 kg $CO_2$eq/kg honey. Zhejiang, Henan, and Shaanxi provinces exhibit lower emissions of 0.032 kg $CO_2$eq/kg honey, 0.086 kg $CO_2$eq/kg honey, and 0.103 kg $CO_2$eq/kg honey, accounting for 4.09%, 9.62%, and 13.7% of the total emissions, respectively. In contrast, higher carbon emissions are reported in Hubei, Sichuan, and Gansu provinces at 0.125 kg $CO_2$eq/kg honey, 0.194 kg $CO_2$eq/kg honey, and 0.17 kg $CO_2$eq/kg honey, representing a share of 17.76%, 21.27%, and 20.83% in the respective total carbon emissions.

## Discussion

Carbon emissions from the TD and TS stages are significant in the context of Chinese honey production. For instance, this study shows that Sichuan province emits 0.366 kg $CO_2$eq/kg honey, while Shanxi province has lower emissions of 0.138 kg $CO_2$eq/kg honey. This variation results from differing transportation distances, with Sichuan province requiring a longer transit of 4418.8 km compared to Shanxi's 1153.5 km. To reduce carbon emissions during transport, this study proposes the adoption of a new energy freight system alongside a transformation in the energy framework of transport vehicles. On the other side, locating beekeeping sites near honey fields is an effective method for reducing carbon emissions linked to the transportation of honey products.

Carbon emissions from the E&P stage are mainly attributed to electricity consumption, with Zhejiang, Henan, and Shanxi experiencing the highest energy-derived emissions. The provinces of Henan and Shanxi exhibit elevated carbon emissions from electricity

Table 5. Carbon emissions of honey in different provinces in China.

| Province | BBM [a] | TD [b] | E&P | TS | Carbon footprint kg $CO_2$eq/kg honey |
|---|---|---|---|---|---|
| Zhejiang | 0.063 (8.05%)* | 0.356 (45.47%) | 0.333 (42.53%) | 0.032 (4.09%) | 0.783 |
| Hubei | 0.032 (4.55%) | 0.366 (51.99%) | 0.181 (25.71%) | 0.125 (17.76%) | 0.704 |
| Henan | 0.045 (5.03%) | 0.351 (39.26%) | 0.412 (46.09%) | 0.086 (9.62%) | 0.894 |
| Sichuan | 0.047 (5.15%) | 0.530 (58.11%) | 0.141 (15.46%) | 0.194 (21.27%) | 0.912 |
| Shanxi | 0.081 (10.77%) | 0.138 (18.35%) | 0.429 (57.05%) | 0.103 (13.7%) | 0.752 |
| Gansu | 0.055 (6.74%) | 0.292 (35.78%) | 0.299 (36.64%) | 0.170 (20.83%) | 0.816 |
| **Average** | **0.054 ± 0.027 (6.85%)** | **0.339 ± 0.201 (40.3%)** | **0.299 ± 0.13 (37.93%)** | **0.118 ± 0.086 (14.92%)** | **0.81 ± 0.106** |

[a] Includes specific emissions from beehive construction, feeding, medication, and pest control.
[b] Includes specific emissions from transports for pollination.
[*] Includes the proportion of the carbon footprint at this stage.
Note: Beehive management (BBM), long-distance transport for pollination (TD), honey extraction and processing (E&P), and transport of processed honey (TS)

generation, primarily due to a high reliance on thermal power generation, the significant importation of electricity from regions with high carbon emissions, and the utilization of high-carbon coal. Although Zhejiang Province is a major consumer of electricity, a substantial proportion of the coal it procures is sourced from other provinces. All these activities result in a higher environmental cost for honey production [41]. This study recommends the promotion of cleaner energy sources and renewable energy sources such as solar, wind, or hydroelectric power for electricity generation. Increasing the share of clean energy in the electricity mix can significantly reduce carbon emissions.

Despite the BBM stage accounting for the smallest percentage of CF, with minimal variation across provinces, the inputs utilized in this stage substantially influence honey quality. Therefore, it is advisable to employ bee medicine moderately. This approach is crucial to prevent quality degradation from excessive residues of bee medicine in honey. Adhering to this recommendation ensures the maintenance of high-quality honey production standards while minimizing environmental impact [42].

For the results of the study, a comparative analysis of similar literature is presented in Fig. 4. In this study, the calculated CF of Chinese honey is 0.81 kg $CO_2$eq/kg

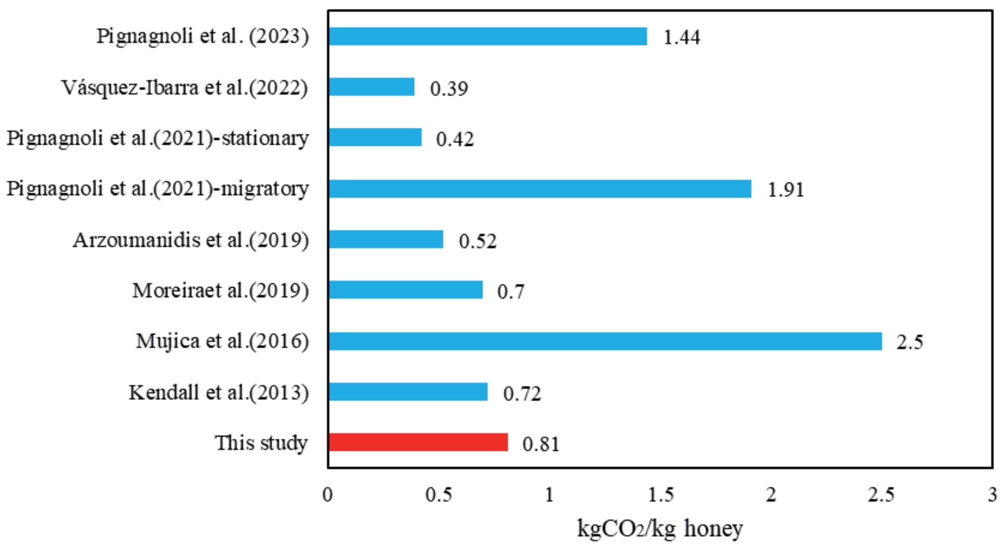


Fig. 4. Comparison of different studies.

honey. When this value is benchmarked against existing research, such as the study by Moreira et al. (2019), it is found to lie in the middle range of the carbon footprint of honey production in the Natural Parks of Northwestern Spain. Compared to the study by Kendall et al. (2013), which reported a CF of 0.72 kg $CO_2$eq/kg honey, our findings indicate a slightly higher figure. Kendall et al. (2013) focused on commercial-scale honey production, while this study focuses on small-scale beekeepers engaged in migratory beekeeping. This study encompasses two distinct phases, "bee travel for nectar and pollen" and "transport for raw honey", which Kendall et al. (2013) deemed inapplicable to small-scale amateur producers and were not included in their study [34, 37]. Mujica et al. (2016) calculated the CF of honey in Argentina using the ISO 14040 methodology, resulting in 2.5 ± 0.17 kg $CO_2$eq/kg honey. This figure is higher than this study's findings, which indicate a CF of approximately 0.299 kg $CO_2$eq/kg honey [35]. In Argentina, honey production is managed through cooperative facilities employed by all provinces. These cooperatives are characterized by higher production capacity and higher total installed power, which lead to increased energy consumption. This increased energy usage is a reason for the significantly higher CF observed in Argentine honey production, as reported by Mujica et al. (2013), compared to the results of our study. Our study parallels that of Moreira et al. (2019), particularly in identifying transport as a major contributor to GHG emissions. However, our study extends beyond the scope of Moreira et al. (2019) by explicitly incorporating the assessment of product transportation to the market. Pignagnoli et al. (2021) conducted a comprehensive study on the CF associated with honey production in both migratory and non-migratory beekeeping systems. The findings indicate that migratory beekeeping systems have a CF ranging from 1.40 to 2.20 kg $CO_2$eq/kg honey, while non-migratory beekeeping systems have a significantly lower CF, with values ranging from 0.380 to 0.48 kg $CO_2$eq/kg honey [36]. In contrast, our study is specifically tailored to the context of Chinese migratory beekeepers, excluding stationary beekeeping practices from the analysis. This could be an avenue for future research and improvement. Vásquez-Ibarra et al. (2022) conducted a cradle-to-gate assessment of 15 midpoint impact categories for honey production by 31 beekeepers in the Maule region of Chile and reported a CF of 0.39 kg $CO_2$eq/kg honey. The primary factor impacting the CF in honey production is the consumption of feed, followed by beehive transport. The substantial divergence from our findings can be attributed to their omission of energy consumption related to beehive construction and honey transport to the market [38]. A more recent study by Pignagnoli et al. (2023) estimated an overall LCA result of 1.44 kg $CO_2$eq/kg honey. Both transport and supplementary feeding were identified as the primary sources of GHG emissions [26]. It is noteworthy that in our study, transport emerged as the main contributor to GHG emissions in China, while emissions from supplementary feeding were negligible. This distinction highlights the varying environmental impacts of different beekeeping practices and contexts.

## Conclusions

Overall, the CF of honey production in China is calculated to average 0.81 kg $CO_2$eq/kg honey. The BBM, TD, E&P, and TS stages contribute 6.85%, 40.3%, 37.93%, and 14.92% to the total CF, respectively. The TD and E&P stages are particularly significant contributors to carbon emissions, collectively accounting for 78.23% of emissions. This high percentage is primarily due to the extensive energy consumption involved in long-distance migratory beekeeping practices prevalent in China and inefficient energy use in small-scale honey extraction and packaging factories. To effectively reduce the CF, a focus on controlling carbon emissions, particularly in the TD and E&P stages is crucial, although attention to the BBM and TS stages is also warranted. At the BBM stage, careful attention to the type and quantity of bee medication can play a crucial role in reducing carbon emissions.

At a provincial level, the CF of honey production in China varied, with the highest to lowest emissions recorded in Sichuan, Henan, Gansu, Zhejiang, Shanxi, and Hubei, showing values of 0.912, 0.894, 0.816, 0.783, 0.752, and 0.704 kg $CO_2$eq/kg honey, respectively. The disparities in carbon emissions are notably influenced by the TD and E&P stages, where large-scale migratory practices from southern to northern regions, driven by the need to follow flowering seasons, result in increased energy consumption. For instance, in southern provinces such as Sichuan, Hubei, and Zhejiang, the carbon emissions attributed to chasing honey sources contribute 58.11%, 51.99%, and 45.47% to their respective CFs. Encouraging stationary beekeeping methods in these areas could potentially reduce the CF of China's honey production. Moreover, differences in electricity carbon emissions factors contribute to variations in the E&P stage across provinces.

Through the research, the following recommendations are proposed:

(1) The following strategies are recommended for honey production stages. The use of certified sustainable forest wood or recycled materials for beehives can be encouraged at the BBM stage to reduce the ecological footprint while promoting the use of renewable energy systems (e.g., solar energy) to power the heating and ventilation of beehives, thereby reducing dependence on fossil fuels.

(2) At the TD stage, optimal routes and timing for bee migration can be identified through various strategies and techniques, such as GIS software and GPS tags, to reduce the distance and number of transports required. The use of more environmentally friendly modes of transport, such as electric or hybrid vehicles for beehive transshipment, can alsoreduce carbon emissions.

(3) At the E&P stage, the use of modern, energy-efficient honey extraction and processing equipment is encouraged to reduce energy consumption, while the utilization of recyclable or biodegradable packaging materials could reduce the carbon footprint of the packaging process.

(4) Logistics planning at the TS stage can be optimized to improve loading rates and distribution efficiency to reduce unnecessary transport round trips. In addition, encouraging consumers to purchase locally produced honey can further decrease the need for long-distance transport and associated carbon emissions.

This study is the first to estimate the carbon footprint (CF) of honey products in China. But limitations include potential underestimation due to data gaps and randomness in sampling. To enhance accuracy, future studies should incorporate more input variables and a larger sample size. Meanwhile, there are limitations associated with establishing system boundaries and developing a life cycle inventory due to a lack of available data. Despite limitations, this study represents the first quantitative analysis of the CF of Chinese honey products, providing valuable insights and addressing a significant research gap in the field. Future work could aim to improve the accuracy of CF calculations through larger samples, diverse beekeeping methods, broader system boundaries, and a comprehensive life cycle inventory. Furthermore, it would be beneficial to explore non-parametric methods for calculating the ecological efficiency of beekeepers' honey production and to understand various factors that influence this efficiency.

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## Conflict of Interest

The authors declare no conflict of interest

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