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CARBON FOOTPRINT ACCOUNTING AND EVALUATION OF AUTOMOTIVE AIR CONDITIONING FILTERS BASED ON LIFE CYCLE ASSESSMENT (LCA)

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Abstract: Driven by the "dual carbon" goals to promote the green transformation of the automotive industry, the full-life-cycle carbon footprint of automotive components has become a core focus of the industry's low-carbon development. This study takes automotive air conditioning filters as the research object. Based on the Life Cycle Assessment (LCA) methodology, it defines the carbon footprint accounting boundary covering the "raw material acquisition - production - transportation - end-of-life" process, constructs a carbon footprint calculation model, and conducts full-life-cycle carbon footprint accounting for three typical automotive air conditioning filters. The results show that the raw material acquisition stage is the main contributor to the carbon footprint of automotive air conditioning filters, accounting for more than 60% of the total. Furthermore, approaches to reduce the product's carbon footprint are proposed, including material substitution, process optimization, energy and auxiliary material upgrading, and waste recycling. The research results provide a theoretical basis and data support for the low-carbon design, production optimization of automotive air conditioning filters, and carbon management of the automotive industry chain.
Keywords: Life Cycle Assessment; Automotive air conditioning filter; Carbon footprint

1 INTRODUCTION

Under the dual impetus of global "dual carbon" goals and the green transformation of the automotive industry, the management and control of the full-life-cycle carbon footprint of automobiles have become a core issue for the sustainable development of the industry[1,2]. As important components contributing to the carbon footprint, automotive parts have gradually become a research focus[3,4]. As a key component to ensure the air quality inside vehicles, automotive air conditioning filters are characterized by short service life, high replacement frequency, and large market demand[5]. The cumulative effect of carbon emissions throughout their full process (production, use, and disposal) cannot be ignored.

At present, a relatively mature system has been formed for LCA research on core automotive components such as engines and power batteries. However, there remains a significant gap in carbon footprint accounting for consumable parts like air conditioning filters. Existing studies mostly focus on a single link (e.g., environmental impact analysis of filter media production) and lack systematic consideration of the full life cycle, which includes "raw material acquisition - component manufacturing - logistics and transportation - end-use - waste disposal"[6,7].

Therefore, this study takes automotive air conditioning filters as the research object, constructs a full-life-cycle carbon footprint accounting model based on the LCA methodology, identifies carbon emission links in each stage and key carbon emission nodes, and provides three case studies to apply the model. The research results can provide directions for filter manufacturers to optimize low-carbon design, offer data support for the automotive industry to formulate carbon footprint management standards for components, and hold important theoretical and practical significance for promoting the green and low-carbon transformation of the automotive industry chain.

2 CARBON FOOTPRINT ACCOUNTING METHOD FOR AUTOMOTIVE AIR CONDITIONING FILTERS

Life Cycle Assessment (LCA) is an environmental impact assessment method defined by the International Organization for Standardization (ISO) 14040/14044 series standards. By quantifying the resource consumption and environmental emissions of a product throughout its "cradle-to-grave" life cycle (raw material acquisition, production, transportation, use, and waste disposal), it identifies key environmental impact nodes and provides a scientific basis for low-carbon design and decision-making[8,9]. Against the background of the green transformation of the automotive industry, LCA has become a core tool for carbon footprint accounting of components, enabling systematic quantification of carbon emissions throughout the process of consumable parts such as air conditioning filters and supporting the low-carbon optimization of the industry chain.

2.1 Definition of Carbon Footprint Accounting Boundary

In accordance with the requirements of the Standard T/CAS 957—2024 Carbon Footprint of Products—Product Category Rules—Automotive Air Conditioning Filters, the system boundary of automotive air conditioning filters shall in principle cover all stages of the life cycle, including the raw material acquisition stage, production stage, transportation stage, and recycling stage. The comparison boundary of automotive air conditioning filters is a part of the system boundary, including the raw material acquisition stage and production stage, to ensure the comparability of carbon footprints among products before delivery. The schematic diagram of the two boundaries is shown in Figure 1.

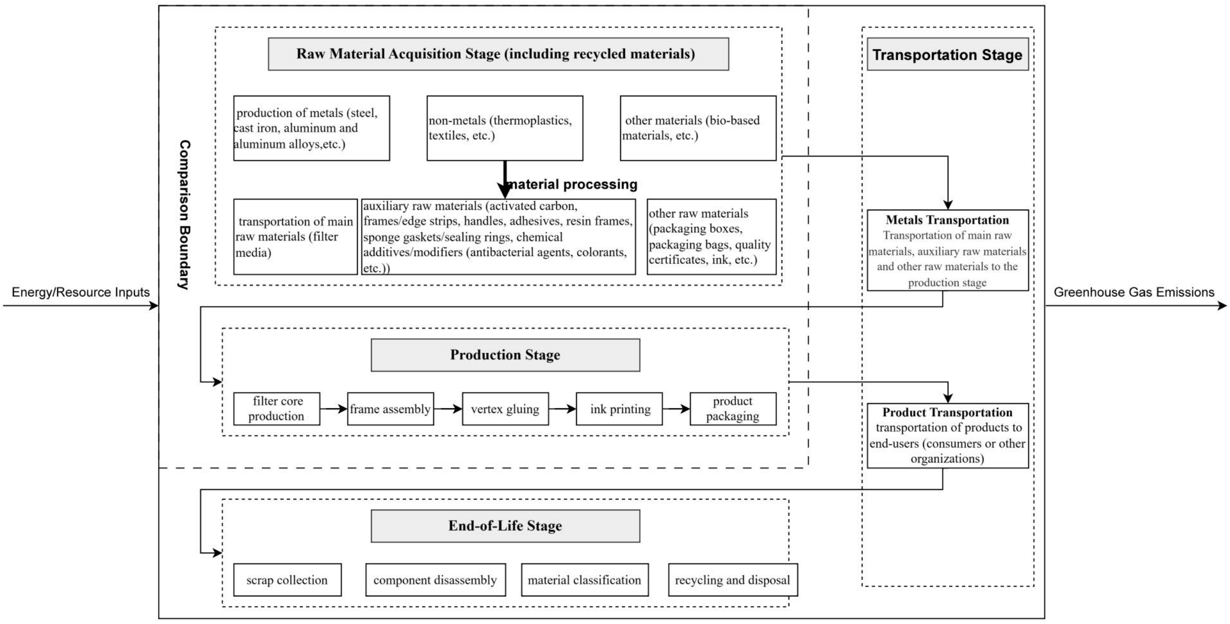

Figure 1 Accounting Boundaries

The raw material acquisition stage begins with the extraction of raw materials and concludes when the raw materials leave the premises of the raw material processing enterprise, encompassing processes such as raw material extraction, processing and purification, and production and processing; meanwhile, the production and processing of recycled materials should include processes like converting waste into recycled materials. The raw materials of automotive air conditioning filters are generally categorized into three types: main raw materials, which are primarily filter media; auxiliary raw materials, including activated carbon, frames (edge strips), handles, adhesives, resin frames, sponge gaskets (sealing rings), and chemical additives/modifiers (such as antibacterial agents and colorants); and other raw materials, which refer to accessories including packaging boxes, packaging bags, quality certificates, ink, instruction manuals, and other packaging materials.

The production stage starts when raw materials enter the premises of the automotive air conditioning filter manufacturing plant and ends when the final product leaves the plant. It mainly includes the total carbon emissions from processes such as filter core production, frame assembly, vertex gluing, ink printing, and product packaging, involving fuel consumption, purchased electricity, purchased heat, and direct emissions. Direct emissions mainly consider the leakage of fire-extinguishing agents and refrigerants. Processes such as product design and investment in production infrastructure are not included in this stage.

The transportation stage consists of two parts: raw material transportation, which starts from when main raw materials, auxiliary raw materials, and other raw materials leave the premises of the raw material production plant and ends when they enter the premises of the air conditioning filter manufacturing plant; and product transportation, which starts from when the products leave the premises of the air conditioning filter manufacturing plant and ends when they enter the premises of distribution centers or sales points.

The end-of-life stage starts when waste automotive air conditioning filters enter the premises of a scrap treatment plant and ends when the product disposal is completed. It mainly includes processes such as collection and management of waste products, disassembly of waste product components, sorting and classification, recycling, and disposal.

2.2 Data Collection and Sources

The data sources for the carbon footprint accounting of automotive air conditioning filters based on Life Cycle Assessment (LCA) are mainly divided into two categories: primary data refers to data obtained by directly measuring or calculating based on direct measurement results to quantify relevant processes or activities, for example, in the raw material acquisition stage, data on the acquisition of main raw materials (such as filter media) and data on energy and resource consumption (such as electricity) in the production stage should be collected as primary data; secondary data refers to data that do not meet the requirements of primary data, including data from databases, published literature, and default emission factors from national databases, for instance, greenhouse gas emission and removal factors related to the transportation link can be collected as secondary data.

2.3 Carbon Footprint Calculation Model

The carbon footprint calculation model for the full life cycle of automotive air conditioning filters is as follows:

$$CFP = C_{\text{Material}} + C_{\text{Production}} + C_{\text{Transportation}} + C_{\text{End-of-Life}} \tag{1}$$

Where:
CFP——Full-life-cycle carbon footprint of an automotive air conditioning filter within the accounting cycle under the system boundary, in kilograms of carbon dioxide equivalent ($kgCO_2e$);
C_{Material}——Carbon emissions from the raw material acquisition stage, $kgCO_2e$;
$C_{\text{Production}}$——Carbon emissions from the production stage, $kgCO_2e$;
$C_{\text{Transportation}}$——Carbon emissions from the transportation stage, $kgCO_2e$;
$C_{\text{End-of-Life}}$——Carbon emissions from the end-of-life stage, $kgCO_2e$.

2.3.1 Raw material acquisition stage

Carbon emissions from the raw material acquisition stage consider emissions from the production and processing of various raw materials, and the model is as follows:

$$C_{\text{Material}} = \sum \left(AD_{\text{i}} \times CEF_{\text{i}} \right) \tag{2}$$

Where:
C_{Material}——Carbon emissions from the raw material acquisition stage, $kgCO_2e$;
AD_i——Quality of raw material i input within the accounting cycle, kg;
CEF_i——Carbon emission factor for the production and processing of raw material i, $kgCO_2e/kg$.

2.3.2 Production stage

Carbon emissions in the production stage consider the total carbon emissions from fuel consumption, purchased electricity, purchased heat, and emissions from the production process (e.g., leakage) during processes such as filter core production, frame assembly, vertex gluing, ink printing, and product packaging. The model is as follows:

$$C_{\text{Production}} = C_{\text{Fuel}} + C_{\text{Electricity}} + C_{\text{Heat}} + C_{\text{Leakage}} \tag{3}$$

(1)Carbon emissions from fuel in the production stage is as follows:

$$C_{\text{Fuel}} = \sum \left(E_{\text{r}} \times CEF_r + E_{\text{r}} \times NCV_r \times CEF_r^{'} \right) \tag{4}$$

Where:
C_{Fuel}——Carbon emissions from fuel combustion in the production stage, $kgCO_2e$;
E_r——Consumption of fuel r, m^3, L, or kg;
CEF_r——Carbon emission factor for the production of fuel r, $kgCO_2e/m^3$, $kgCO_2e/L$, $kgCO_2e/kg$;
CEF'_r——Carbon emission factor for the use of fuel r, tCO_2e/GJ;
NCV_r——Average net calorific value of fuel r, GJ/t, $GJ/10^4m^3$.
Carbon emissions from purchased electricity in the production stage is as follows:

$$C_{\text{Electricity}} = \sum \left(AD_{\text{i}} \times CEF_{\text{i, Electricity}} \right) \tag{5}$$

Where:
$C_{\text{Electricity}}$——Carbon emissions from purchased electricity production in the production stage, $kgCO_2e$;
AD_i——Purchase volume of electricity type i, kWh;
$CEF_{i,\text{Electricity}}$——Carbon emission factor for the production of electricity type i, $kgCO_2e/kWh$.
Carbon emissions from purchased heat in the production stage is as follows:

$$C_{\text{Heat}} = \sum \left(AD_{\text{i}} \times CEF_{\text{i, Heat}} \right) \tag{6}$$

Where:
C_{Heat}—— Carbon emissions from purchased heat production in the production stage, $kgCO_2e$;
AD_i——Purchase volume of heat type i, GJ;
$CEF_{i,\text{Heat}}$——Carbon emission factor for the production of heat type i, $kgCO_2e/GJ$.
Direct leakage mainly considers carbon emissions from greenhouse gas leakage of fire-fighting equipment and refrigeration equipment is as follows:

$$\begin{aligned} C_{\text{Leakage}} = &\sum \left(AD_{\text{i, fire-fighting}I} \times \eta_{\text{fire-fighting}I} \times GWP_{\text{i}} \right) \\ &+ \sum \left(AD_{\text{i, refrigeration}R} \times \eta_{\text{refrigeration}R} \times GWP_{\text{i}} \right) \end{aligned} \tag{7}$$

Where:
C_{Leakage}——Carbon emissions from direct leakage of fire-fighting equipment and refrigeration equipment in the production stage, $kgCO_2e$;
$AD_{i,\text{fire-fighting I}}$——Filling amount of the i-th type of greenhouse gas in fire-fighting equipment I, kg;
$\eta_{i,\text{fire-fighting I}}$——Leakage coefficient of the i-th type of greenhouse gas in fire-fighting equipment I;
$AD_{i,\text{refrigeration R}}$——Filling amount of the i-th type of greenhouse gas in refrigeration equipment R, kg;

$\eta_{i,refrigeration\ R}$——Leakage coefficient of the i-th type of greenhouse gas in refrigeration equipment R;
GWP_i——Global warming potential of the i-th type of greenhouse gas;

2.3.3 Transportation stage

Carbon emissions from the transportation stage is as follows:

$$C_{\text{Transportation}} = \sum \left(AD_{\text{i,r}} \times L_{\text{i,r}} \times CEF_{\text{r}} \right) \tag{8}$$

Where:
$C_{\text{Transportation}}$——Carbon emissions from the transportation stage, $kgCO_2e$;
$AD_{i,r}$——Quality of the i-th type of goods (including raw materials and air conditioning filter products) transported by the r-th type of transportation mode, t;
$L_{i,r}$——Transportation distance of the i-th type of goods transported by the r-th type of transportation mode, km;
CEF_r——Carbon emission factor of the r-th type of transportation mode, $kgCO_2e/(t\cdot km)$.

2.3.4 End-of-life stage

Carbon emissions in the end-of-life stage include emissions from recycling and disposal is as follows:

$$C_{\text{End-of-Life}} = \sum \left(AD_{\text{i}} \times CEF_{\text{i}} \right) + \sum \left(AD_{\text{r}} \times CEF_{\text{r}} \right) \tag{9}$$

Where:
$C_{\text{End-of-Life}}$—— Carbon emissions in the end-of-life stage of the product, $kgCO_2e$;
AD_i——Quality of waste treated by the i-th type of waste disposal method, kg;
CEF_i——Carbon emission factor of the i-th type of waste disposal method, $kgCO_2e/kg$.
AD_r——Quality of the r-th type of recycled material, kg;
CEF_r——Carbon emission factor of the r-th type of recycled material, $kgCO_2e/kg$.

3 ACCOUNTING RESULTS

In this study, the carbon footprint data for three distinct types of automotive air conditioning filters (i.e., Product A, Product B, and Product C) were collected, calculated, and statistically analyzed in line with the calculation model outlined above.

According to the accounting model, the carbon footprints of Product A, Product B, and Product C in the comparison phase are 435.32 gCO_2e, 1087.90 gCO_2e, and 936.00 gCO_2e, respectively. Specifically, for Product A: carbon emissions in the raw material acquisition stage are 267.88 gCO_2e, accounting for 62% of its total product carbon footprint. Among this, the filter media and frames contribute 91% to the carbon footprint of the raw material acquisition stage. The carbon emission during the production stage is 167.44 gCO_2e, accounting for 38% of the product's total carbon footprint. For Product B: carbon emissions in the raw material acquisition stage are 967.14 gCO_2e, accounting for 89% of its total product carbon footprint. Among this, the filter media and frames contribute 76% to the carbon footprint of the raw material acquisition stage. The carbon emission during the production stage is 120.76 gCO_2e, accounting for 11% of its total carbon footprint. For Product C: carbon emissions in the raw material acquisition stage are 896.13 gCO_2e, accounting for 96% of its total product carbon footprint. Among this, the filter media and frames contribute 90% to the carbon footprint of the raw material acquisition stage. The carbon emission during the production stage is 39.87 gCO_2e, accounting for 4% of its total carbon footprint. The emission status of each product is presented in the table below and Figure 2.

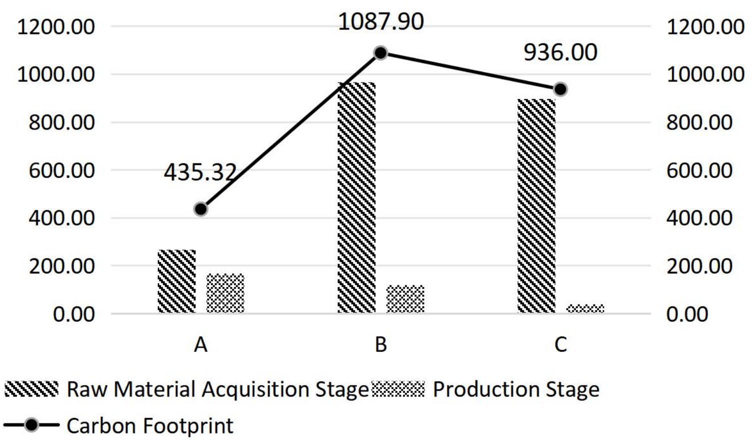

Figure 2 Product Carbon Footprint Analysis Chart (gCO_2e)

4 CONCLUSIONS

Based on the Life Cycle Assessment (LCA) method, this study conducted carbon footprint accounting for three

automotive air conditioning filters. The proposed model can distinguish the carbon footprints of different products.
Taking a medium-sized factory as an example: If the annual production capacity of automotive air conditioning filters is 500,000 units, the total annual carbon footprint of the products would be 220tCO_2e if the carbon footprint of a single product is relatively low (0.44kgCO_2e), and 545tCO_2e if the carbon footprint of a single product is relatively high (1.09kgCO_2e). These figures indicate that the carbon emissions are not negligible, further confirming the necessity of managing the carbon footprint of automotive air conditioning filters.
This study shows that the carbon footprint of automotive air conditioning filters can be effectively reduced from the following three aspects:
(1) At the product design stage, process optimization involves adopting a modular detachable design and green, low-energy-consuming processes. Multiple filter media with different functions are used, and each medium is made of either a single recyclable chemical component or multiple easily separable chemical components to improve the filter element design. This provides convenience for recycling during the production of filter elements and their disposal after use, thereby reducing the consumption of resources and energy.
(2) The raw material acquisition stage is the main contributing link to the carbon footprint of automotive air conditioning filters throughout their entire life cycle, accounting for more than 60% of the total carbon footprint. Among the raw materials, filtering and supporting materials—such as PP (polypropylene), PET (polyethylene terephthalate), and activated carbon—account for more than 75% of the carbon emissions from raw materials. Replacing traditional virgin raw materials with bio-based filter materials or recycled materials can significantly reduce the extraction burden of virgin resources and the carbon emissions generated during raw material production.
(3) At the product production stage, electricity is the main energy source. The indirect emissions from electricity use in the production process can be greatly reduced by two measures: first, replacing thermal power with solar energy or wind energy for production; second, using high-efficiency equipment to reduce energy consumption. In addition, classifying and collecting leftover materials generated from processes such as filter material cutting and frame injection molding during production, then crushing and reintroducing these materials into the production line, can reduce raw material waste and thereby lower the product’s carbon footprint.
These measures can effectively manage the key nodes of carbon footprints, and provide a scientific basis and feasible path for the low-carbon design of automotive air conditioning filters as well as carbon management in the component industry chain.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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