# Life-cycle environmental engineering assessment of closed-loop recycling of automotive headlamp plastics based on LCC–LCA coupling

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Abstract: From the perspective of environmental engineering, the high-value recovery and closed-loop recycling of plastics from end-of-life vehicles (ELVs) represent an important pathway for reducing solid-waste generation, resource consumption, and life-cycle carbon emissions in the automotive sector. In response to domestic and international requirements for circular-economy development and recycled-content management, this study selects automotive headlamp plastics as a representative waste-plastic stream and constructs a full-chain closed-loop recycling pathway covering ELV dismantling, plastic recovery and pelletizing, material modification, and re-application in new vehicles. An LCC–LCA coupling framework is used to evaluate both the economic feasibility and life-cycle environmental performance of the pathway. The results provide environmental-engineering evidence and practical demonstration support for improving automotive waste-plastic resource recovery, reducing carbon emissions, and promoting high-value material circulation in China's automotive industry.

Keywords: environmental engineering; end-of-life vehicles; waste plastic recycling; closed-loop recycling; life cycle assessment; life cycle cost; carbon footprint; resource recovery

## 1. Introduction

Against the backdrop of China's continued pursuit of the "dual-carbon" targets, the circular economy has emerged as a critical pathway for green and low-carbon transition. As an industry characterized by intensive resource consumption and substantial environmental emissions, the automotive sector increasingly regards the utilization rate of secondary resources throughout the vehicle life cycle as an essential indicator of sustainable development.[1,2] The proportion of plastic materials used in automobiles has risen steadily in recent years, with extensive application in components such as lighting systems, instrument panels, and interior parts. However, the recycling and recovery of these high-value plastics in China's end-of-life vehicles (ELVs) stage remain in their infancy, facing challenges such as complex dismantling processes, insufficient material purity, and limited market acceptance.

Globally, regions such as Europe and the United States have taken the lead in elevating automotive plastics recycling and reuse to the regulatory level. In September 2025, Members of the European Parliament adopted the revised EU ELV Regulation, which mandates that within six years of its entry into force, plastics used in each new vehicle model must contain at least 20% recycled content, of which 15% must originate from

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ELVs.[3] This policy not only poses significant challenges to the automotive value chain within the EU but also exerts substantial compliance pressure on China's export-oriented automotive supply chain. Existing studies indicate that if plastic components cannot be effectively recycled and reused during ELV treatment, substantial resource losses and environmental burdens will result.

Beyond the need to meet domestic and international policy and compliance requirements, the environmental implications of recycled plastics and the associated cost impacts across the automotive value chain warrant careful attention.[4]

In addition to regulatory pressures, the adoption of recycled plastics introduces new economic burdens, technical uncertainties, and market acceptance barriers for upstream and downstream enterprises. These factors collectively constrain large-scale application and underscore the need for more comprehensive assessments and systematic solutions.[5]

Accordingly, this work is positioned within environmental engineering, with emphasis on waste-plastic resource recovery, closed-loop material circulation, and life-cycle environmental assessment rather than on automotive manufacturing alone.

# 2. Research Background and Significance

## 2.1 Current Status of Recycled Materials Application in the Automotive Sector

This study focuses on recycled plastics recovered from end-of-life vehicle headlamp assemblies. In 2024, China recorded 8.46 million ELVs collected nationwide, representing a year-on-year increase of 64%. Among them, 7.872 million were de-registered automobiles, marking a 70.7% growth compared with the previous year and reflecting the sustained rapid expansion of the industry. The total mass of automobiles scrapped in 2024 is estimated at approximately 11 million tonnes, from which roughly 710,000 tonnes of waste plastics were recovered during the dismantling process.

Recycled plastics produced from dismantled automotive plastics mainly include recycled PP, PE, PVC, ABS, and PC. Through material modification or blending with virgin plastics, these recycled materials exhibit partial overlap and functional substitutability with their virgin counterparts. Certain relatively homogeneous categories, after high-quality mechanical recycling, can even be reapplied to their original automotive uses.[6]

Several automotive manufacturers have already incorporated recycled materials into new-vehicle production. For instance, 89% of the interior fabrics in the Audi A3 are made from recyclable PET bottles, with each seat produced from forty-five 1.5-L PET bottles. Jaguar Land Rover has collaborated with ECONYL to introduce recycled nylon into automotive interior materials. NIO has developed renewable rattan-based materials and the Clean+ fabric—made entirely from recycled plastic bottles—and applied them to the ET5 model's secondary instrument panel, reducing carbon emissions by more than 30% compared with conventional materials.

Meanwhile, materials manufacturers are accelerating their deployment in the automotive recycled-materials market. Following the release of the EU's proposed revised ELV Regulation, companies such as Honeywell, Dow, Covestro, Borealis, and SABIC have joined forces with upstream and downstream partners to actively expand their portfolios of recycled automotive materials.

## 2.2 Key Existing Challenges

### *2.2.1 High Costs of Recycled Plastics*

Labor costs at the ELV dismantling stage are relatively high, while plastics account for only a small fraction of total dismantled materials. As a result, many dismantling enterprises choose not to conduct fine sorting, instead prioritizing the sale of scrap steel. Additionally, due to the lack of stable downstream recyclers, certain plastics are purchased by individuals at waste-material prices, resulting in a fragmented supply structure characterized by elevated labor and logistics costs.

To improve transportation efficiency, plastic recyclers need to crush plastic components into small flakes or pellets. However, this process requires multiple sets of equipment—such as washing systems, flotation separation, electrostatic separation, shredding, and color sorting—requiring total investments of several million RMB, which presents a substantial financial burden for small and medium-sized enterprises.

Moreover, technical challenges persist at the plastic regeneration stage. During processing, the color of plastics tends to darken progressively, restricting the applicability of mechanically recycled materials to low-value, downgraded uses (e.g., dark-colored waste bins) rather than enabling their reuse in original automotive applications, thus significantly diminishing their value.

### *2.2.2 Inefficient Recycling Processes*

Automobiles consist of diverse materials and complex structures, making fine-grained classification difficult during dismantling. In the absence of stable supply–demand relationships and supporting incentive mechanisms, dismantling enterprises often choose to compact plastics together with the vehicle body or treat them as mixed waste, rather than investing additional labor and cost into separation. This situation limits recyclers' access to stable and controllable feedstock and prevents the formation of a closed-loop recycling system, thereby constraining the broader adoption of recycled plastics in the automotive industry.

### *2.2.3 Underdeveloped Standards and Regulatory Framework*

China currently lacks mandatory regulations and standards specifically targeting automotive recycled plastics, and the recycling system remains at an early stage. Some enterprises express concerns that domestic and international standards may not be mutually recognized, creating duplicated efforts to comply simultaneously with EU certification requirements and domestic standards. Others are reluctant to provide data to foreign certification bodies due to concerns about data leakage and loss of proprietary information.

## 2.3 Research Objectives and Significance

Life-cycle analyses comparing 2010 and 2020 indicate that advances in energy systems and production technologies have contributed to a lower carbon footprint in virgin plastic manufacturing. Amzan Alsabri et al.[7] evaluated the environmental impacts of polypropylene production using life-cycle assessment (LCA), estimating carbon emissions of virgin plastics at approximately 1,580 kg $CO_2$e per tonne based on real plant operational data, and proposed potential technological improvements. Nordahl S et al.[8] assessed life-cycle emissions from recycled and virgin plastics under different recycling methods, finding that mechanical recycling reduces emissions by approximately 80% compared with virgin plastics (equivalent to ~316 kg $CO_2$e per tonne). Alsabri et al.[9] further summarized LCA studies on PP production and recycling in the Gulf region, identifying the carbon-emission profiles of various pathways. Existing research—both domestic and international—has largely focused on the carbon reduction benefits of recycled plastics. However, few studies have evaluated the economic viability or jointly assessed the environmental and economic benefits of recycled-plastic application.[10]

Building on a collaborative pilot project jointly implemented by automakers (Volkswagen, NIO), ELV dismantling enterprises (GEM), plastic recycling companies (Ausel), and material-modification enterprises (Covestro), this study conducts a closed-loop analysis of the entire recycling chain of waste automotive headlamp plastics—including vehicle dismantling, headlamp dismantling and plastic recovery, material modification, performance testing, and application in new vehicles. Through comprehensive economic and environmental assessments, the study evaluates the feasibility of high-value recycling pathways for automotive plastics. The findings aim to provide practical demonstration experience and policy recommendations for advancing the standardization and industrialization of China's automotive plastic recycling system.[10]

Therefore, the research objective is to provide an environmental-engineering evaluation of the closed-loop recycling pathway for ELV-derived automotive plastics, linking process-chain design with carbon-footprint reduction and cost-effectiveness.

## 2.4 Overview of the Demonstration Project on Plastic Recycling and Reuse

This project encompasses all key stages of the automotive plastic recycling value chain, including ELV dismantling, plastic recovery and pelletizing, material modification, and the re-application of recycled plastics in new vehicles. Using automotive headlamps as a representative component, the project establishes a relatively complete technical pathway for closed-loop recycling.

ELV dismantling: At the ELV recycling facilities, headlamp assemblies are carefully removed from ELVs to avoid mixing plastics with other materials, thereby improving recovery efficiency and feedstock purity.

Plastic recovery: Recycling enterprises clean, shred, sort, and pelletize the dismantled headlamp plastics to produce reusable recycled plastic pellets.

Modification and development: Material-modification enterprises enhance the recycled pellets by improving impact resistance, thermal stability, and processing performance, enabling the material to meet the performance requirements for automotive components.

Application and validation: Automotive manufacturers utilize the modified recycled plastics to reproduce plastic components and install them in new vehicles. A series of laboratory tests are conducted to verify the material's reliability in terms of safety, durability, and environmental performance.

Certification and evaluation: Independent third-party certification bodies supervise and certify the entire project process to ensure scientific rigor, transparency, and international credibility.

Through the participation of upstream and downstream enterprises as well as certification institutions, a collaborative framework with clear responsibilities has been established. This process enables plastics recovered from ELVs to be reused in new vehicles—achieving a "vehicle-to-vehicle" closed-loop recycling model (As shown in Figure 1).

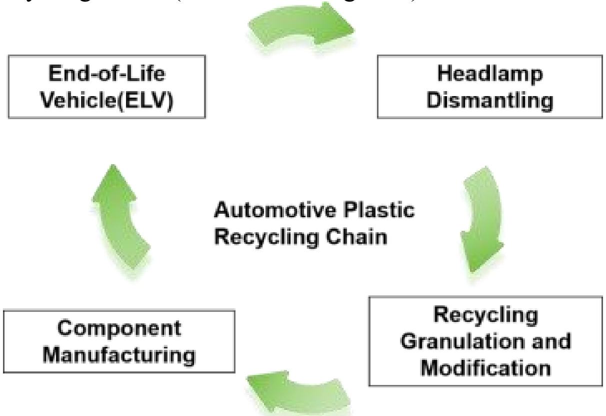

**Figure 1.** Closed-loop framework of end-of-life vehicle (ELV) recycling and material circulation

## 2.5 Environmental Engineering Assessment Methodology

### *2.5.1 Research Object and Functional Unit*

The study focuses on the closed-loop recycling pathway for automotive plastics, covering the major stages involving ELV dismantling enterprises, plastic recycling and pelletizing enterprises, material-modification companies, and automotive manufacturers (performance verification and application). The functional unit (FU) is defined as 1 tonne of modified recycled plastic that meets automotive application requirements. The baseline scenario for comparison is virgin plastic with equivalent performance and specifications.

### *2.5.2 System Boundary*

A cradle-to-gate system boundary is adopted for both the recycled plastic pathway and the virgin plastic baseline scenario. The system boundary covers all processes required to produce 1 tonne of automotive-grade polycarbonate (PC) material ready for component manufacturing.

For the virgin plastic pathway, the system boundary includes the following processes:

- production of polycarbonate resin from fossil-based feedstock,
- polymerization and pellet production,
- transportation of virgin plastic pellets,
- injection molding and component manufacturing.

Energy consumption, auxiliary materials, and transportation are included in these processes.

For the recycled plastic pathway, the system boundary includes:

- ELV dismantling and headlamp removal,
- headlamp disassembly and plastic sorting,
- washing, shredding, and pelletizing of recovered plastics,
- material modification and compounding,
- transportation between recycling stages,
- injection molding and component manufacturing.

To ensure comparability, identical downstream manufacturing processes are assumed for both virgin and recycled plastic scenarios.

Although the processing steps differ between the virgin and recycled plastic pathways, the system boundaries remain consistent. For virgin plastics, costs are primarily associated with raw material procurement and injection molding processes, whereas the recycled plastic pathway involves additional stages such as dismantling, pelletizing, and material modification. Both pathways ultimately produce the same functional output—automotive-grade plastic materials for component manufacturing—and therefore maintain consistent system boundaries for both the LCA and LCC analyses.

## 2.6 Life Cycle Cost (LCC) Calculation

### *2.6.1 Cash-Flow Perspective*

Let the discount rate be denoted by r, and the analysis period be T years. The cost and benefit in year t are denoted by $C_t$ and $B_t$, respectively.

$$\mathrm{NPV}=\sum_{t=0}^{T}\frac{B_t\text{-}C_t}{(1+r)^t} \tag{1}$$

$$\mathrm{LCC}=\sum_{t=0}^{T}\frac{C_t\text{-}B_t}{(1+r)^t}=\text{-NPV} \tag{2}$$

$$\mathrm{UC}=\frac{LCC}{Q_{FU}} \tag{3}$$

where NPV is the net present value, LCC is the total life cycle cost, $U_C$ is the unit product cost (expressed per functional unit), and $Q_{FU}$ is the cumulative production over the analysis period converted into functional units.

### *2.6.2 Segmented (Stage-wise) Costs*

The costs and benefits are calculated separately for the four stages of dismantling, pelletizing, modification, and in-vehicle application, with $i\epsilon$(dismantling, pelletizing, modification, in-vehicle application)

$$C_i=C_i^{\mathrm{raw}}+C_i^{\mathrm{energy}}+C_i^{\mathrm{labor}}+C_i^{\mathrm{depreciation}}+C_i^{\mathrm{transport}}+C_i^{\mathrm{disposal}}\text{-}S_i^{\mathrm{byproduct}} \tag*{(4))}$$

$$B_i=B_i^{\mathrm{sales}}+S_i^{\mathrm{subsidy}} \tag{5}$$

where $C_i$ denotes the cost of stage i, $B_i$ denotes the revenue of stage i, and $S_i$ represents the additional (incremental) revenue generated at stage i.

## 2.7 Life Cycle Environmental Assessment (LCA)

### *2.7.1 Life Cycle Inventory (LCI)*

Process environmental load:

$$I_j^c=\sum_k A_{j,k}\cdot EF_{j,k}^c \tag{6}$$

where: j denotes the unit process (e.g., dismantling, washing, shredding, pelletizing, modification, validation, transportation, waste treatment, etc.).$A_{j,k}$represents the annual activity level for flow type k within process j (including electricity, natural gas, water, additives, transport tonne - kilometers, wastewater, solid waste, etc.).$EF^c_{j,k}$, is the corresponding impact factor for impact category c (primarily GWP).

$$I^c=\sum_j I_j^c \tag{7}$$

where $I^c$ represents the total environmental impact.

Note:Recycled materials entering the system do not carry upstream burdens from their virgin-material life cycle. Only the environmental loads associated with current recovery and reprocessing are included.

### *2.7.2 Normalization to Functional Unit*

The total impact is divided by total output and converted to one functional unit (FU), followed by the calculation of the difference relative to the baseline (recycled – virgin).

$$EI_{FU}^c=\frac{I^c}{Q_{FU}} \tag{8}$$

$$\Delta EI_{FU}^c=EI_{FU,recycled}^c\text{-}EI_{FU,virgin}^c \tag{9}$$

where:

$\mathrm{EI}^{\mathrm{c}}_{\mathrm{FU,recycled}}$ is the impact per functional unit for the recycled-material scenario,

$\mathrm{EI}^{\mathrm{c}}_{\mathrm{FU,virgin}}$ is the impact per functional unit for the baseline virgin-material scenario.

## 3. LCC–LCA Coupling and Cost per Unit of Emission Reduction

To integrate economic performance with carbon-reduction benefits, the unit abatement cost (UAC) is calculated.

If UAC < 0, the recycled pathway is “cost-saving and emission-reducing”.

If UAC > 0, the value represents the marginal cost required to achieve emission reduction.

$$\mathrm{UAC}=\frac{\Delta LCC_{FU}}{-\Delta EI_{FU}^{c}} \tag{10}$$

$$\Delta LCC_{FU}=LCC_{FU,recycled}-LCC_{FU,virgin} \tag{11}$$

where: $\mathrm{LCC}_{\mathrm{FU,recycled}}^{\mathrm{c}}$ is the life cycle cost per functional unit of the recycled-material pathway, $\mathrm{LCC}_{\mathrm{FU,virgin}}$ is the life cycle cost per functional unit of the baseline scenario.

### 3.1 Data Sources

The LCI data used in this study were obtained from a combination of industrial pilot project data, established life cycle databases, and peer-reviewed literature sources.

Primary data for the recycling pathway were collected from enterprises participating in the closed-loop demonstration project, including ELV dismantling enterprises (GEM), plastic recycling enterprises (Ausell), and material modification enterprises (Covestro). These data include energy consumption, material inputs, transportation distances, and process yields during dismantling, pelletizing, and modification processes.

Secondary environmental data for virgin polycarbonate (PC) production were referenced from life cycle assessment literature and the EcoInvent database.[11] The dataset “polycarbonate production, granulate, at plant” was used to represent the environmental burdens associated with virgin PC production.

Market price data for virgin PC were obtained from Echemi and were used exclusively for the life cycle cost (LCC) analysis.[12]

Energy consumption during injection molding processes was referenced from the EcoInvent, which reports an average electricity consumption of approximately 1.47 kWh per kg of processed plastic.[11]

Carbon emission factors for virgin plastics were cross-validated using published literature. Alsabri et al. reported that the life cycle greenhouse gas emissions of virgin polypropylene production are approximately 1,580 kg $CO_2$-eq per tonne, while mechanical recycling can reduce emissions by approximately 80% compared with virgin production.

## 4. Environmental and Economic Impact Assessment of the Recycling Pathway

Building on the construction of the material-circulation pathway and the verification of material performance in the demonstration project, this study conducts a comparative evaluation of two alternative pathways—virgin material production and recycled material application—within the manufacturing process of automotive plastic components. Through a combined life cycle cost (LCC) and life cycle environmental impact (LCA) analysis, the study examines the advantages of recycled plastics in terms of resource conservation, cost reduction, and carbon-footprint mitigation.

### 4.1 Cost Analysis of Virgin Plastics

In the virgin material production pathway, the total manufacturing cost can be expressed as:

$$\mathrm{C_{virgin}=C_{raw}+C_{energy}+C_{labor}+C_{equipment\ depreciation}+C_{transport}} \tag{12}$$

### 4.2 Raw Material Procurement Cost

$$\mathrm{C_{raw}}=\sum_{\mathrm{i}}(\mathrm{P_i}\times\mathrm{Q_i}) \tag{13}$$

where: Pi is the market price of raw material category i (yuan/ton), Qi is the quantity of raw material i used in headlamp manufacturing.

Automotive headlamps typically consist of several major components, including reflectors, lenses, housings, light sources, electronic circuits, and mounting accessories. The primary raw materials used in headlamp production in China include polycarbonate (PC), polymethyl methacrylate (PMMA), aluminum alloy, and glass. According to market data, the price of virgin PC is approximately 14,250 yuan/ton (equivalent to 2,000–2,300 USD/ton).[12]

In this study, the cost comparison between virgin PC and recycled PC is used as the baseline. Therefore, the raw material cost of virgin PC is calculated as:

$$\mathrm{C_{PC\ virgin}=14250\ yuan/ton}$$

### 4.3 Production Cost

Figure 2 provides an overall summary of the cost structure of virgin and recycled plastics. It shows that virgin plastics mainly incur raw material procurement costs, whereas recycled plastics involve cumulative costs from dismantling, recycling, and modification. Overall, the figure highlights that the cost difference between virgin and recycled plastics arises from the multi-stage processing chain required for recycled materials.

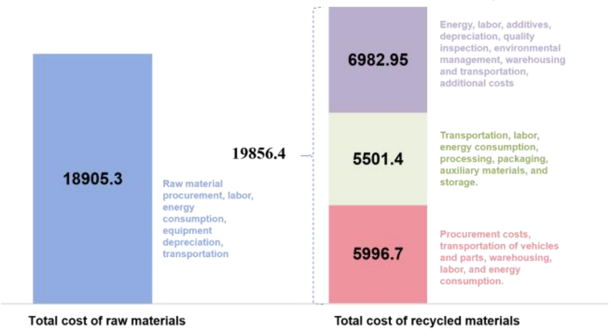

**Figure 2.** Cost composition and stage-wise breakdown of virgin versus recycled plastics

$$C_{\text{production}} = C_{\text{energy}} + C_{\text{equipment depreciation}} \tag{14}$$

**(1)Energy Consumption**

The energy consumption of injection molding can be referenced from life cycle inventory (LCI) databases. According to EcoInvent, the average electricity consumption of injection molding is approximately 1.47 kWh/kg. Other studies report a range of 1.0–2.1 kWh/kg.[13] For engineering estimations, a typical reference range is 0.8–1.2 kWh/kg (i.e., 800–1200 kWh/ton).

Assuming an electricity price of 0.8 yuan/kWh, the energy cost per tonne of plastic is: $C_{\text{energy}}$=640–960 yuan/ton(midpoint: 800 yuan/ton)

**(2)Equipment Depreciation**

$$C_{\text{depreciation}} = \frac{P_{\text{equipment}} - P_{\text{residual}}}{T_{\text{lifetime}} \times Q_{\text{annaul}}} \tag{15}$$

where:$P_{\text{equipment}}$ is total equipment investment, $T_{\text{lifetime}}$ is depreciation period (typically 5–8 years), $P_{\text{residual}}$ is recovery/salvage value, $Q_{\text{annual}}$ is annual production output.

Example: For a 320-ton clamping force injection molding machine, the commonly used Haitian MA3200 model costs USD 50,000–58,400 (equivalent to 360,000–420,000 yuan).[14] Assume:annual production Q is 800 tons/year.

Substituting values:

$$C_{\text{depreciation/year}} = \frac{400000\text{-}126000}{8*800} = \frac{274000}{6400} = 42.8 \text{ yuan/ton}$$

$$C_{\text{production}} = C_{\text{energy}} + C_{\text{depreciation}}$$
$$= 800 + 42.8 = 842.8 \text{ yuan/ton}$$

### 4.4 Labor Cost

$$C_{\text{labor}} = \frac{N_{\text{workers}} \times N_{\text{hours}} \times W_{\text{hour}} \times H_{\text{year}}}{Q_{\text{annual}}} \tag{16}$$

Where $N_{\text{workers}}$ is the number of production-line workers (assumed to be 5), $N_{\text{hours}}$ is the daily working hours (8 hours/day), $W_{\text{hour}}$ is the average hourly wage (23–28 yuan/hour according to the Ministry of Industry and Information Technology, with 25 yuan/hour used here), $H_{\text{year}}$ is the annual working hours per worker (approximately 250 working days/year), and $Q_{\text{annual}}$ is the annual processing volume of headlamp plastics (800 tons/year).

Substituting:

$$C_{\text{labor}} = \frac{5 \times 8 \times 25 \times 250}{800} = 312.5 \text{ yuan/ton}$$

### 4.5 Transportation Cost

$$C_{\text{transport}} = \sum_j (Q_j \times D_j \times P_{\text{freight}}) \tag{17}$$

where $Q_j$ is the transported mass, $D_j$ is the transport distance (km), and $P_{\text{freight}}$ is the unit freight rate per ton·km. The national average for road transportation is about 10 yuan/ton·km. The average transport distance is assumed to be 200–500 km.

$$C_{\text{transport}} = 10 \times 350 = 3500 \text{ yuan/ton}$$

### 4.6 Total Production Cost of Virgin Plastics

$$LCC_{FU,virgin} = C_{\text{raw}} + C_{\text{energy}} + C_{\text{labor}} + C_{\text{depreciation}} + C_{\text{transport}}$$
$$= 14250 + 842.8 + 312.5 + 3500 = 18905.3 \text{ yuan/ton}$$

### 4.7 Cost Analysis of Recycled Plastics

This study collected detailed cost data for transportation, storage, and processing across various stages of the recycling chain from ELV dismantling enterprises (GEM), plastic recycling enterprises (Ausell), and material-modification enterprises (Covestro). As these data involve internal corporate operations, the specific numerical values are not reported here.

### 4.8 Costs of ELV Dismantling Enterprises

Dismantling enterprises test and clean intact (or reusable) headlamp assemblies removed from ELVs and transfer them to downstream processes. The cost items include ELV acquisition cost, vehicle and component transportation, storage, labor, and energy consumption. Based on pilot enterprise feedback, the total cost for this stage is 5,996.7 yuan/ton.

### 4.9 Costs of Plastic Recycling Enterprises

After dismantling, headlamp plastics enter the recycling chain, where they undergo pelletizing and related processes before being transferred to the next stage. Costs include transportation, labor, energy consumption, processing, packaging, auxiliary materials, and storage. Based on pilot enterprise feedback, the total cost for this stage is 5,501.4 yuan/ton.

### 4.10 Costs of Plastic Modification Enterprises

After being pelletized, the recycled plastics enter the modification stage, where modified materials are supplied to automotive manufacturers for new-vehicle production. Costs include energy, labor, additives, depreciation, quality inspection, environmental management, storage, and transportation. Additional cost is considered to account for batch variability, testing, formulation adjustments, and yield losses. Based on pilot enterprise feedback, the total cost for this stage is 6,982.95 yuan/ton.

$$LCC_{FU,recycled} = (C_{\text{dismantling}} + C_{\text{recycling}}/0.8 + C_{\text{modification}}) =$$
$$19856.4 \text{ yuan/ton}$$

where an 80% qualified-product rate is assumed for recycled pellets.

## 5. Economic and Environmental Coupled Benefits

### 5.1 Cost of Emission Reduction

$$\Delta LCC_{FU} = LCC_{FU,recycled} - LCC_{FU,virgin} = 19856.4$$
$$-18905.3 = 951.1 \text{yuan/ton}$$
$$\Delta EI^{c}_{FU} = EI^{c}_{FU,recycled} - EI^{c}_{FU,virgin} = 316 - 1580$$
$$= -1264 \text{kgCO2e/t}$$

$$\mathrm{UAC}=\frac{\Delta LCC_{FU}}{-\Delta EI_{FU}^{c}}=\frac{951.1}{1264}=0.75\ \mathrm{yuan/kgCO2e}$$

This indicates that the use of recycled plastics by automotive manufacturers leads to emission reductions but also increases costs, with a unit abatement cost of 0.75 yuan/kg $CO_2e$.

### 5.2 Forecast of Compliance Costs for Enterprises

According to CATARC forecasts, China's automobile production will reach 37.24 million vehicles by 2031 (six years after the EU ELV Regulation comes into force). If China adopts similar management targets—requiring plastics used in new vehicles to contain at least 20% recycled content, of which 15% must originate from ELVs—and assuming an average vehicle mass of 1.4 tons,[15-17] the additional compliance cost is calculated as follows:

37.24 million×1.4×20%×15%×951.1=1,487,596,000 yuan

That is, by 2031, Chinese automotive enterprises would bear over 1.4 billion yuan in compliance costs to meet the relevant policy requirements.

## 6. Conclusions and Outlook

### 6.1 Conclusions

This study presents an environmental engineering assessment framework for the closed-loop recycling of automotive headlamp plastics from end-of-life vehicles by coupling life cycle cost (LCC) and life cycle assessment (LCA) methods. By taking the ELV headlamp-plastic recovery, pelletizing, modification, and re-application chain as the research object, the study evaluates both the resource-recovery feasibility and carbon-reduction performance of a high-value waste-plastic recycling pathway. The results indicate that:

(1) By 2031, six years after the enforcement of the EU ELV Regulation, if China aligns its management indicators with the EU targets, Chinese automotive manufacturers will incur more than 1.4 billion yuan in compliance costs.

(2) Under current technological and industrial conditions, the cost of recycled plastics is slightly higher than that of virgin plastics, with an incremental cost of approximately 951 yuan per ton. The corresponding unit abatement cost is 0.75 yuan/kg $CO_2e$, significantly higher than the trading prices in China's voluntary greenhouse gas market. This suggests that although recycled plastics offer clear carbon-reduction advantages, their economic performance still requires further optimization.

(3) Labor and logistics expenditures, equipment investment, and performance variability after modification represent the primary factors influencing the economic viability of recycled plastics. Enterprises may reduce recycling costs and improve economic feasibility by enhancing automation, optimizing logistics systems, and advancing relevant technologies.

### 6.2 Outlook

In the future, with continuous technological innovation, improved governmental management mechanisms, and the refinement of industry standards, recycled automotive plastics are expected to play a critical role across the automotive value chain, with further potential for cost reduction. The following actions are recommended:

(1) Governmental management: It is recommended that relevant authorities accelerate the release of regulatory documents specifying the application ratios of recycled automotive materials, thereby allowing sufficient time for technological upgrading and industrial restructuring among Chinese automotive manufacturers. Fiscal subsidies, tax incentives, and green credit mechanisms may be adopted to encourage enterprises to actively employ recycled materials and reduce associated costs.

(2) Enterprise operations: Enterprises are encouraged to enhance fine-sorting capabilities and promote large-scale recycling of waste plastics. Increasing investment in sorting technologies, recycling processes, and material-modification R&D will be essential for reducing recycling costs.

(3) Industry development: Industry associations and related organizations should accelerate the improvement of standards, certification systems, and traceability frameworks, including the development of core standards such as the Guidelines for Traceability Management of Recycled Automotive Materials, clarifying material classification, utilization ratios, and traceability requirements. The application of blockchain technologies should be promoted to establish a full-process traceability system covering materials, components, and vehicles. In addition, collaborative platforms involving government, industry, academia, and research institutions should be enhanced to support demonstration projects such as "closed-loop recycling of high-value automotive plastics," thereby addressing the persistent challenge of high-value component loss.

## Acknowledgements

The authors would like to thank all participating enterprises and experts for providing valuable data and technical support throughout the demonstration project. We also appreciate the constructive discussions that contributed to the improvement of this study.

## Funding:

Guangxi Major Special Project Program-Key Technologies Research and Industrialization of the Application Ecosystem for New Energy Vehicle Power Batteries (Grant No. Guike AA23062082).

## Authors' Contributions

All authors contributed to the study conception, methodology design, data analysis, and manuscript writing.

Material preparation and data collection were performed by Qingyao Meng, Jia Wang, Yingli Ren, Yueyan Zhu

The overall project supervision, manuscript revision, and final approval were completed by Jia Wang.

All authors have read and approved the final manuscript.

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