Life Cycle Assessment of Footwear Production under Sustainable Design Scenarios

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Introduction

The footwear industry is a typical example of labor intensive and resource consuming sectors. This industry faces serious issues of resource waste and environmental pollution. Approximately 80% of the environmental impact of footwear is determined during the product design stage (European Commission, 2020). Therefore, it is essential to develop sustainable design for footwear products. Key entry points for sustainable footwear design include renewable material substitution and production process optimization. Designing product packaging that is easy to recycle or biodegrade is another important approach (Gajewski et al., 2014). In addition, additive manufacturing (also known as 3D printing) is receiving wide attention, that serves as a reduction solution for traditional manufacturing (Graziosi et al., 2024).

However, the footwear industry faces a "black box" problem regarding process level data. There is also a lack of synergy between sustainable design schemes. These issues make it difficult for companies to establish precise development paths. To address this, this study constructs a life cycle environmental impact assessment framework based on refined unit processes. This framework solves the long standing "process data black box" in footwear production. Furthermore, this study analyzes the response characteristics of various environmental indicators under single or combined sustainable design scenarios. The results provide a precise scientific basis for companies to optimize production workflows. This research also offers a universal reference framework for the sustainable development of labor intensive manufacturing.

Material and methods

This study evaluates the environmental impact of producing one pair of size 41 basketball footwear. The evaluation follows the life cycle assessment methods in international standards ISO 14040:2006 and ISO 14044:2006.

The study links the complex background material list precisely to the foreground production processes. This approach avoids the mechanical separation between material acquisition and manufacturing stages common in traditional LCA research. Figure 1 shows the system boundary. The research models the production using GaBi software. It calculates environmental impacts using the CML 2001 method based on midpoint analysis from Leiden University. This study sets eight scenarios and analyzes their environmental impact characteristics. Table 1 shows the scenarios and parameter settings.

Table 1. Sustainable design scenarios and parameter settings

Scenarios	Description	Baseline scenario indicators	Parameter settings
S1	Upper material substitution scenario	PET fiber fabric	PLA fiber fabric
S2	Upper reduction scenario	Synthetic leather, fabric upper	3D printing (TPU)
S3	Sole reduction scenario	Traditional adhesive assembly	Mortise and tenon jointing
S4	Packaging reduction scenario	Virgin pulp corrugated box	50% reduction in packaging
S5	Packaging material substitution scenario		Recycled pulp corrugated box
S6	Renewable substitution scenario		S1 & S5
S7	Reduction scenario		S2 & S3 & S4
S8	Combined scenario		S1 & S2 & S3 & S4 & S5 (The consumable for 3D printed upper is PLA)

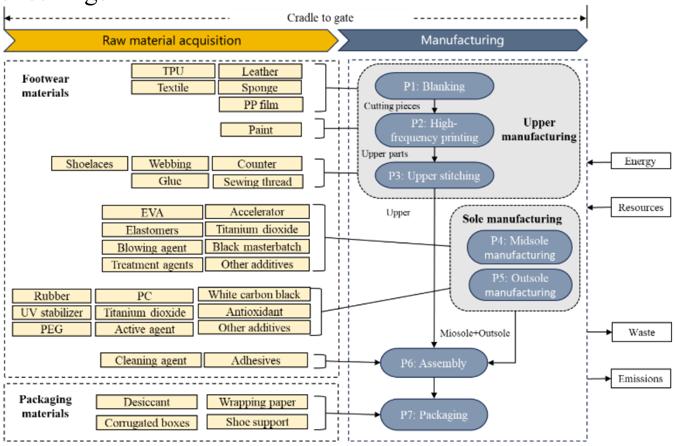

Figure 1. System boundary

Results and discussion

The study calculates the environmental impacts of basketball footwear at different production stages. The results show that all environmental impacts from the raw material acquisition stage are greater than those from the manufacturing stage. Textile and the main component of the sole are key hotspots for environmental impact.

As shown in Figure 2 (a-d), among the seven production processes, P1 contributes the most (55%), followed by P2 (16%) and P5 (11%). The blanking(P1) and sole manufacturing(P4+P5) processes bear higher impacts. The high-frequency printing(P2) process has a significant impact on greenhouse gas emissions (about 20%) due to its heavy reliance on electricity consumption.

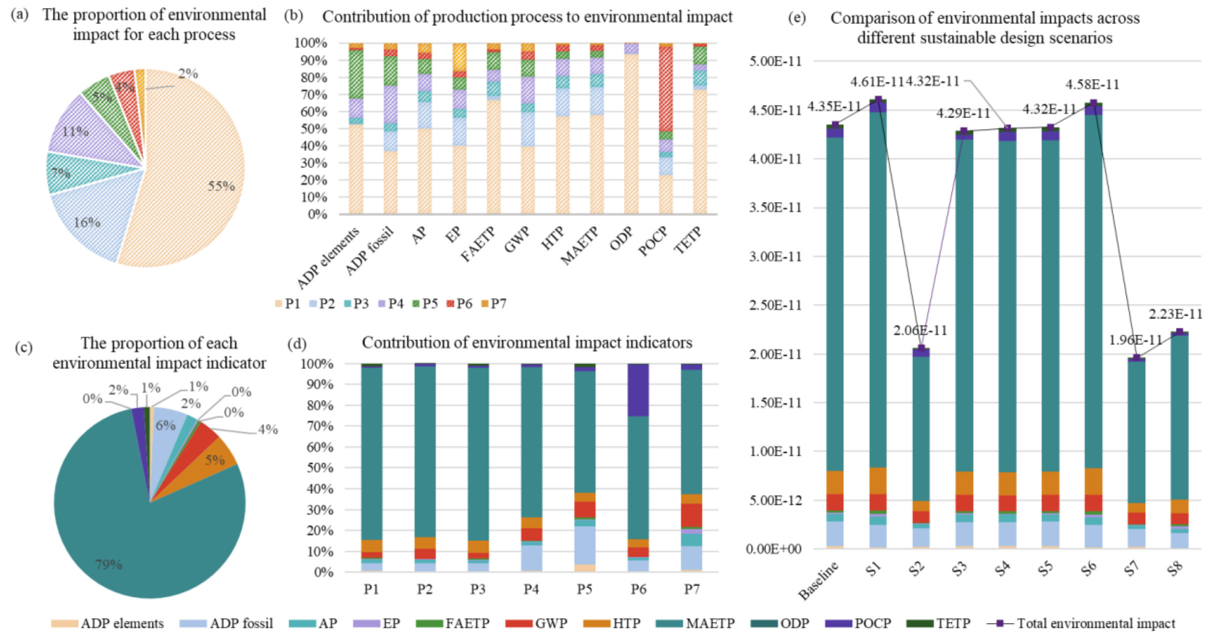

Figure 2. Environmental impact results. (a-d) Results based on process division. (e) Comparison across different sustainable design scenarios.

As shown in Figure 2 (e), both S1 and S5 reduce resource dependence through material substitution. S1 is inferior to S5 because the ecological cost of PLA during the agricultural stage is a major drawback. Among the three reduction strategies (S2, S3, and S4), S2 shows the best performance. Multiple indicators under S2 improve significantly. S3 only has a significant impact on POCP. S4 reduces raw material waste, but its overall performance remains stable. The comprehensive performance of S6, S7, and S8 is ranked as S7 > S8 > S6.

The research results highlight the short-term hidden costs of PLA due to agricultural production, as well as the long-term social risks of process innovation arising from the displacement of traditional labor. Therefore, sustainable design should integrate technical innovation with Life Cycle Assessment (LCA) rather than simply stacking technologies, thereby avoiding the scenario where short-term advantages in a single indicator mask long-term systemic risks, or where temporary risks in a single indicator obscure systemic advantages.

Conclusions

The conclusions of this study include: (1) Raw material acquisition is the core environmental burden, contributing 68% of the total environmental impact. (2) S7 shows the best short term benefits. It can reduce the total environmental load to 45% of the baseline. (3) Bio-based materials such as PLA have heavy agricultural production burdens. Their advantages depend heavily on degradation management at the end of the life cycle. (4) Simple stacking of technologies does not lead to a linear increase in environmental benefits. Strategy combinations require synergistic optimization of technologies.

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