Proceedings of the ASME 2025 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC2025
August 17–20, 2025, Anaheim, CA

DETC2025-169019

DATA-DRIVEN SUSTAINABLE DESIGN OPPORTUNITIES FROM AUTOMATED USER INSIGHTS

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ABSTRACT

Qualitative data from user interactions with products provide a rich source of sustainability insights, revealing how users perceive and interact with sustainable product features. However, users often describe sustainability in terms of personal experiences rather than technical environmental terminology, making it challenging to extract structured insights. As a result, analyzing this feedback to inform future product design is valuable but often labor-intensive. This research explores how data-driven techniques can automate and enhance the generation of sustainable product design insights from user feedback. We constructed a database of over 23,000 Amazon customer reviews for 290 consumer products and analyzed it using aspect-based sentiment analysis (ABSA), topic modeling, and large language models (LLMs). Combining traditional NLP methods with generative models, we identified sustainability-related product concerns and valued features. A case study highlights how this approach generates product-level insights, synthesizing sustainable design leads comparable to manually-derived ones for a printer, laptop, and cable. Our findings demonstrate that users tend to focus on tangible, personal-use aspects of sustainability, such as packaging and waste reduction, while overlooking more technical concerns like manufacturing processes. We also demonstrate the ability to generate design leads tailored to specific product features, such as printer toner or earring material properties. As the volume of user feedback grows, this research highlights the need for efficient methods to identify trends, uncover redesign opportunities for enhanced sustainability, and improve how sustainability is communicated through product features and user experiences, creating a valuable resource for future research.

Keywords: sustainable design, user-centered design, design theory and methodology

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Documentation for `asmeconf.cls`: Version 1.38, May 30, 2025.

1. INTRODUCTION

Eliciting user needs and understanding user feedback are essential steps in the design process, influencing product development, innovation, and long-term market success [1, 2]. Gathering and interpreting user needs help designers create products that align with user expectations while addressing functional and emotional requirements [3]. Traditionally, methods such as interviews, surveys, and observations have been employed to capture these insights. However, as digitalization expands across design industries, the increased availability of product data and user feedback presents new opportunities to incorporate user perspectives into the design process, particularly in improving the usability, communication, and adoption of sustainable products [4].

In particular, integrating sustainability considerations into design is an ongoing challenge in design for sustainability (DfS) and sustainable product-service system (S-PSS) research [5, 6]. In this work, we focus on environmental sustainability, which we define as *the effect an engineered product has on the natural world* [7]. Although sustainability-driven design frameworks such as life cycle analysis (LCA) and circular design emphasize objective environmental impact assessments of a given product, service, or system, there is growing recognition that user perceptions and behaviors play a critical role in the success and adoption of sustainable products [8–10]. Understanding how users perceive and respond to sustainability-related features can offer critical insight into both how such products are experienced and how their sustainability is communicated.

However, users are more likely to describe sustainability aspects of a product in terms of their personal experiences and usage rather than using formal environmental terminology like carbon emissions or water usage [11]. This makes the extraction of sustainability-related insights from user feedback inherently contextual, interpretive, and perception-driven. Users also rarely discuss upstream life cycle factors, like manufacturing processes or material sourcing, because these technical details fall outside their direct experience, which limits the depth of feedback. Rather than replacing technical assessments, user reviews can reveal how

sustainability features are received in practice and expose gaps between certification standards and user understanding.

Despite the abundance of online user product feedback, the challenge lies in effectively navigating and leveraging this growing volume of data to inform design decisions and better position sustainable products for users. The emergence of natural language processing (NLP) techniques has significantly enhanced the ability to analyze unstructured text data at scale. Previous work has explored how NLP techniques like topic modeling can be integrated into "human-in-the-loop" systems to identify patterns in user feedback and highlight areas for sustainable product improvement [11–13]. However, traditional NLP methods often require significant preprocessing and manual interpretation, limiting their scalability and accessibility to designers without technical expertise.

Recent advancements in large language models (LLMs) present an opportunity to automate the extraction of design-relevant insights from textual data. These models can capture nuanced relationships between product features, user sentiment, and sustainability concerns, enabling a more comprehensive understanding of user needs and expectations. In this work, we combine LLMs with traditional NLP techniques to systematically extract insights from online product reviews, focusing on sustainability-related themes. By structuring these insights around product features, we aim to bridge the gap between unstructured user feedback and actionable design recommendations. Rather than replacing expert judgment, this approach supports designers by surfacing patterns in user perceptions of sustainability, especially those related to the communication, experience, and perceived value of sustainability. This can support designers by identifying how users interpret and experience sustainability, turning user feedback into actionable insights.

The goal of this research is to explore how data-driven techniques can support the generation of insights that inform both sustainable redesign efforts and strategies to improve how sustainability is communicated and perceived. To this end, we generate and analyze a database of customer reviews from a large online retailer, using large language models to extract valuable user insights alongside product features. By exploring this approach, we contribute to the growing field of data-driven sustainable design and address the traditionally manual, time-intensive task of extracting and integrating user insights into sustainability-oriented design processes. This approach enables quick, large-scale processing across different products through context-aware automation.

The primary contributions of this work are:

- Creating a database of product reviews and information for use in future sustainable design research.
- Identifying sustainability trends across product categories to support both design and communication strategies.
- Automating the process of identifying sustainable design insights from user feedback and product information, enabling a scalable method to generate insights from existing data.

Though this paper focuses on environmental sustainability, the approach can naturally extend to other pillars of sustainability (social and economic) by adapting the analysis to identify features like labor conditions, ethical sourcing concerns, cost considerations in user feedback, etc.

In this paper, we first review related work that contextualizes our study (Sec. 2). We then describe our research methodology (Sec. 3), and present results and discussion from our database (Sec. 4). Finally, we present our case study (Sec. 5) and discuss future directions for this work (Sec. 6).

2. RELATED WORK

In this section we review related work on eliciting user needs, design for sustainability, and how online reviews are used to inform sustainable design.

2.1 Eliciting user needs

Eliciting user opinions and customer needs is an essential part of the *planning* stage of the human-centered design process [1]. Traditionally, this has been done through interviews, focus groups, observations, and surveys. However, online product reviews offer a vast, yet unstructured, source of user feedback. These reviews have been seen as valuable data sources for a many tasks around characterizing users and their needs, with a variety of natural language processing techniques being used to extract insights. For example, Mokadam et al. used aspect-based sentiment analysis (ABSA) to extract user requirements from a set of Amazon reviews [14]. This work showed the promise of using automated techniques to surface user needs. Similar work sought to identify latent user needs from reviews [15–17], or those that are not explicitly stated by the user, but otherwise inferred from their context [18, 19]. These papers combine product attribute identification with forms of sentiment analysis and abstractive summarization to identify potential use cases from users and subsequently derive user needs. However, these approaches used traditional NLP techniques and required expert oversight or fine-tuning of models. Our approach foregoes model fine-tuning and seeks to uncover user needs by combining a previously-used approach, ABSA, with the context-aware capabilities of LLMs.

Additional opportunities for using online reviews as a data source for user insights include identifying use cases [20], which helps identify product improvements and market opportunities, through rule-based classification. Finally, reviews have been used for the task of customer segmentation [21, 22]. By creating networks of customer embeddings, designers can cluster existing users and better inform their design process, creating products that are a better fit for users.

2.2 Design for Sustainability

The human-centered product design process typically consists of six stages: planning, concept development, system-level design, detailed design, testing and refinement, and production [1]. However, the literature is divided on which stage is most critical for integrating environmental sustainability [23, 24]. Telenko et al. propose that most sustainable design tools can be broadly classified as focused on either 1) life cycle analysis (LCA) or 2) Design for Environment (DfE) [25]. LCA provides a systematic

method for quantifying the environmental impact of a product, process, or service [26], but requires a depth of detail about a product that is often not available during early-stage design. DfE, on the other hand, is a subfield of product design concerned with systematically considering a design's performance within the context of sustainability throughout its life cycle [27]. DfE guidelines [25] provide a set of actionable, designer-oriented rules that can support the early stages of the design process during or even before idea generation. Ross, Ferrero, and DuPont showed that providing designers with structured DfE strategies during conceptual design can increase the breadth of sustainable design decisions made [28]. Given the abundance of user data available, there is a clear need to effectively leverage these resources to support sustainable development and better inform the design process [29]. By grounding sustainable design leads in real user feedback, this research aims to support the DfE process and provide actionable insights for sustainability-driven design.

2.3 Using online reviews to inform sustainable design

Previous literature has explored various techniques for how online product reviews can be leveraged to provide sustainability insights [30]. El Dehaibi, Goodman, and Macdonald associated user sentiment with sustainability features through crowdsourcing and manual annotations [12], identifying which features were perceived both positively and negatively by consumers. They observed a gap between a product's "actual" sustainability and its perceived sustainability. Additional work sought to use human annotators to extract sustainable design recommendations for consumer electronics [11]. This work was limited by the manual process needed to annotate reviews for mentions of sustainability and extract insights from them, providing a challenge for scaling this method. Machine learning techniques were later used to extract design for repairability insights from online product reviews [13]. Though most of the work focuses on using user feedback to inform sustainable design (including this paper), it does not necessarily take into account the "true" environmental impact of the products being analyzed. Studies show that a gap exists between users' perceptions of sustainability and ecological reality [12, 31, 32]. To address this, Saidani et al. looked to combine user reviews with life cycle assessment (LCA) data to bridge the gap [33]. These papers point toward the promise of using topic modeling techniques to reveal areas where designers may focus their efforts given increased user attention. Our research looks to build upon this work and harness the capabilities of novel LLMs, whose natural language capabilities have revolutionized text and other data sources can be interacted with. By doing so, we can scale the extraction of these insights and make them more personalized and relevant to individual designers and products within the design process.

3. METHODS

This study explores how data-driven sustainability insights can be extracted at scale by combining traditional NLP techniques with LLM-based approaches. Figure 1 outlines the process: customer reviews from 290 certified consumer products are analyzed using sentiment analysis and topic modeling to identify key themes. LLMs then synthesize sustainability insights, and categorical sentiment trends are examined across product types. A case study on consumer electronics compares LLM-generated design leads to manual insights from Saidani et al. [11], demonstrating how this hybrid approach supports sustainable product redesign.

Sustainability Certification	Description
Blue Angel	Consumer products that meet high environmental standards, including protecting consumers' health.
BIFMA	Furniture products based on corporate, facility, and product manufacturing processes against environmental impact, health and wellness, and social responsibility criteria.
Forest Stewardship Council	Products contain wood-based material that is harvested using practices that better protect the environment.
Recycled Claim Standard 100	Certifies recycled content (>95%) that has been independently verified at each stage of the supply chain, from the source to the final product.

TABLE 1: SUMMARY OF SUSTAINABILITY CERTIFICATIONS THAT THE PRODUCTS ANALYZED FALL UNDER.

3.1 Database construction

To explore data-driven techniques for extracting sustainability insights, a database of Amazon customer reviews was created. The analysis focused on products that hold sustainability certifications, as these certifications indicate some level of established sustainability within the product itself. A summary of these certifications is provided in Table 1. Amazon's Climate Pledge Friendly label highlights products certified by a range of external agencies[1]. These products are marked with a leaf icon on their pages, signaling to users that they meet specific sustainability criteria. The selected certifications were chosen to ensure diversity across product categories while maintaining a focus on sustainability.

3.1.1 Product Selection Criteria. Products were selected based on their certification and categorized into various product groups (as labeled by Amazon) to ensure a representative sample across industries. The distribution of products is outlined in Table 2. This distribution ensures a comprehensive dataset across diverse product types and sustainability certifications.

3.1.2 Data Extraction. A custom web scraper was developed to collect both product information and customer reviews from Amazon. The scraper adhered to ethical data collection practices, including compliance with Amazon's `robots.txt` guidelines. 50 reviews per star category were extracted (i.e.

[1] https://www.amazon.com/b?ie=UTF8&node=21221608011

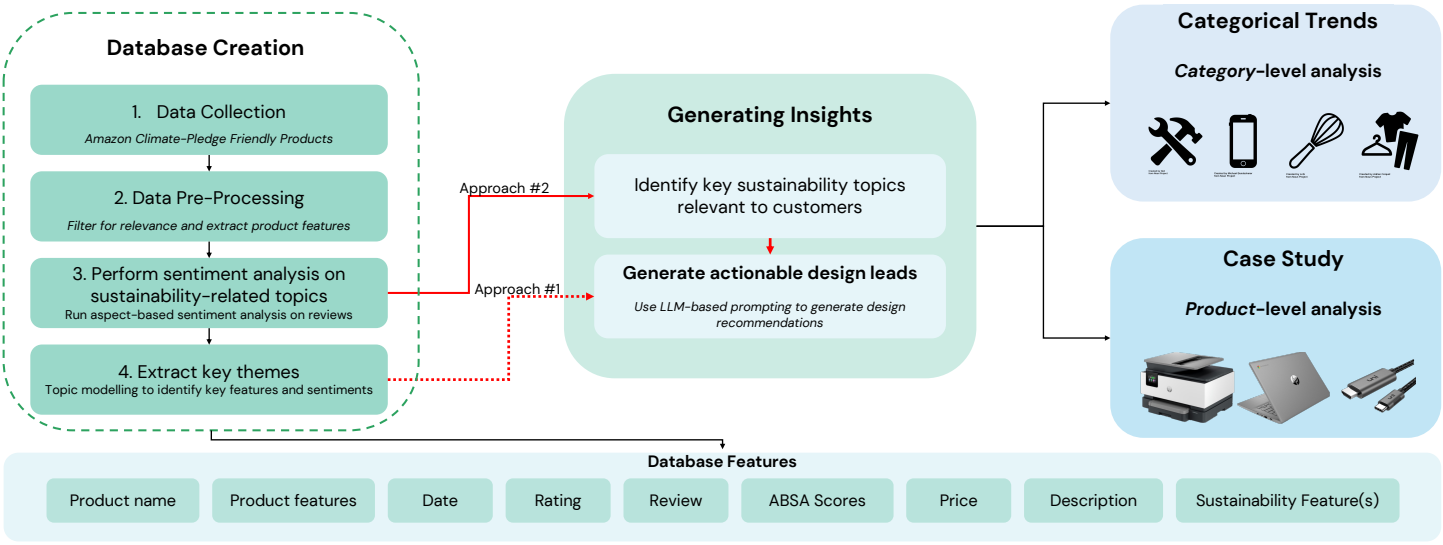

FIGURE 1: OVERVIEW OF METHODS FOR GENERATING SUSTAINABLE DESIGN INSIGHTS FROM USER FEEDBACK. A DATABASE OF SUSTAINABILITY-CERTIFIED PRODUCTS WAS CREATED AND ANALYZED USING TWO APPROACHES: (1) TOPIC MODELING AS INPUT TO AN LLM TO GENERATE THEMATIC INSIGHTS (DASHED RED LINE) AND (2) ASPECT-BASED SENTIMENT ANALYSIS AS INPUT TO AN LLM TO EXTRACT INSIGHTS FROM POLARIZING SUSTAINABILITY CATEGORIES (SOLID RED LINE). WE PRESENT CATEGORICAL TRENDS OF THE FULL DATABASE AND A CASE STUDY OF THREE DISTINCT PRODUCTS FOR PRODUCT-LEVEL ANALYSIS.

Sustainability Certification	Product Categories
Blue Angel	Appliances, Electronics, Home & Kitchen, Office Products, Tools & Home Improvement
BIFMA	Electronics, Home & Kitchen, Industrial & Scientific, Office Products, Tools & Home Improvement
Forest Stewardship Council	Appliances, Beauty & Personal Care, Home & Kitchen, Office Products, Tools & Home Improvement
Recycled Claim Standard 100	Cell Phones & Accessories, Clothing, Shoes & Jewelry, Electronics, Home & Kitchen, Tools & Home Improvement

TABLE 2: DISTRIBUTION OF PRODUCTS ACROSS CERTIFICATIONS AND CATEGORIES.

50 5-star reviews, 50 4-star reviews, etc.) for each product, as available. The following features were extracted from the product information: product name, price, description, sustainability features (certifications), average user rating, number of reviews, product page URL. The features extracted from the reviews are: review URL, user rating, author name, date of review, review content.

3.1.3 Data Cleaning and Preprocessing. To ensure consistency and quality in the dataset, non-English reviews were identified and removed. Reviews with less than five words were removed for quality. Additionally, to gain a deeper understanding of the products' sustainable design attributes, product descriptions were analyzed using OpenAI's GPT-4.o model to extract product features. The definition for product features was derived from prior literature extracting features and affordances from customer reviews [34]. This linguistically defines product features as: *the nouns that describe product components and attributes, as well as the linking verbs adjacent to a product name or product component*. To verify this approach, we iterated the prompt phrasing we used on a "training set" (10%) of the review database. Then, the authors manually annotated 100 reviews across all aspects and found 98% agreement with the model. Disagreements arose primarily related to reviews about product durability, which was flagged as an area for future refinement.

3.1.4 Aspect-Based Sentiment Analysis (ABSA). Aspect-Based Sentiment Analysis (ABSA) was conducted on the broader database of products across product categories and certifications. This approach dissected reviews to identify sentiments linked to distinct sustainability-related aspects of each product. These aspects were inspired from a set of 164 sustainability-related keywords previously developed by sustainability researchers [33]. The keywords were thematically grouped into 16 high-level sustainability aspects. They covered the following sustainability topics: General Sustainability, Material, Packaging, Environment, Energy, Manufacturing Process, User Experience. A full list of the sustainability aspects and definitions that were used can be found in the appendix (Appendix A).

For each aspect, each review was assigned sentiment scores based on explicit and implicit cues in the review text: 1 (positive sentiment), 0 (neutral or no mention), and -1 (negative sentiment). OpenAI's GPT-4.o model was used to classify these reviews, and the prompt used can be found in Appendix B. This granular anal-

Sustainability Certification	Number of Reviews
Blue Angel	2468
BIFMA	3894
Forest Stewardship Council	11305
Recycled Claim Standard 100	6213

TABLE 3: NUMBER OF REVIEWS BY SUSTAINABILITY CERTIFICATION.

ysis provided insights into specific strengths and weaknesses of products concerning sustainability, pointing to areas of importance which have the potential for high impact among users.

3.1.5 Database features. After cleaning and processing the reviews using the NLP techniques explained above, the resulting database was comprised of 290 consumer products, with a total number of reviews as seen in Table 3. For each product review, the following information is presented: product name, price, product description, sustainability features (as rated by their certification), product features, overall product rating, date, user rating, user review, and ABSA scores.

3.2 Certification Analysis

To assess whether sustainability certifications align with user concerns, we analyzed the ABSA results across certified products. This analysis aimed to determine whether users discuss the same sustainability aspects that a certification emphasizes and whether certified products receive more positive sentiment in those aspects, indicating alignment with user expectations.

We reviewed the official description of each certification to identify which aspects they prioritize. For example, the Forest Stewardship Council (FSC) focuses on responsible sourcing of wood-based materials, while the Recycled Claim Standard 100 (RCS 100) certifies that products contain at least 95% verified recycled materials. For each certification, we categorized which of the sustainability aspects were directly related to the official description, indicating areas that these products should technically perform well in.

To compare user sentiment across certifications, we analyzed:

- The number of reviews mentioning each sustainability aspect for each certification, assessing whether users actively discuss the same aspects the certification promotes.
- The proportion of positive vs. negative sentiment within each aspect, measuring whether certified products perform well in the areas they claim to support.

To quantify this, we computed the positive sentiment ratio for each certification:

$$\text{Positive sentiment ratio} = \frac{\text{Positive Reviews}}{\text{Positive Reviews+Negative Reviews}} \times 100\% \quad (1)$$

This analysis provides insight into whether certifications effectively reflect user expectations or if gaps exist between certification claims and real-world user perception.

3.3 Generating Insights

For each product category, sentiment-driven trends were identified. These trends were then used as inputs into the GPT-4.o model to synthesize which product features are perceived as valued vs areas of improvement. To generate these sustainable design leads, two approaches were used. The first approach applied topic modeling to the reviews, extracting key themes, which were then used as inputs for an LLM prompt. The second approach leveraged the ABSA results, identifying peaks in sentiment trends and selecting reviews from these peaks as inputs for an LLM prompt. By structuring insights around sustainability topics, prompts became more targeted, and data inputs were categorically grouped, allowing for more precise and actionable findings. While both methods aim to surface relevant insights, the topic modeling approach captures broader thematic trends, whereas the ABSA-based approach focuses on highly polarized user sentiments. This intra-category analysis refined the connections between sentiment trends and sustainability-related themes, ensuring that the generated design leads were both contextually relevant and directly applicable to product redesign efforts.

3.3.1 Topic Modeling-Driven Insights. First, Latent Dirichlet Allocation (LDA) was used to uncover overarching themes across product reviews. LDA was chosen for its ability to identify latent topics in large text datasets without predefining categories, ensuring an unbiased extraction of key discussion points from user reviews.

Reviews were first grouped by product category within each certification, and LDA was performed on these groups, capturing category-specific concerns. Since different certifications cover different product ranges, topics were then combined across certifications within the same product category to retain information without losing insights from certification-specific differences.

To focus on sustainability-related insights, GPT-4.o was used to filter the extracted topics, identifying those that directly pertain to sustainability. This allowed for the creation of actionable sustainability leads, which were then manually reviewed by one design researcher using the sustainability dictionary in Appendix A to ensure their relevance and accuracy for informing product redesign.

3.3.2 ABSA-Driven Insights. In parallel, outputs from the ABSA process were leveraged to extract sentiment-driven insights, which were then synthesized using GPT-based topic analysis to identify nuanced trends and actionable insights. Design failures were flagged when negative sentiment and topic frequency converged on specific product features. Similarly, features associated with positive sentiment and high-frequency mentions were highlighted as successful design elements. These insights were further contextualized within a sustainability framework to propose opportunities for sustainable redesign.

To operationalize this, and to help provide focused inputs to the model for improved actionable results, reviews were filtered by ABSA sentiment. For a given product category, ABSA categories with large sentiment peaks were identified. For positive sentiment peaks, reviews which were tagged as having positive sentiment in that category were fed into GPT-4.o and prompted to identify the successful design elements present in this category.

The model was required to justify these elements by presenting relevant review fragments. On the other hand, for negative peaks, reviews which were tagged as having negative sentiment in this category were fed into GPT-4.o and prompted to identify areas of improvement that were present in this category. Again, the model was required to justify these elements by presenting relevant review fragments. The prompt used to generate these leads can be found in Appendix C.

4. RESULTS AND DISCUSSION

In this section, we present findings on our database, including user perceptions of sustainability certifications and how our proposed method can generate design leads at a categorical-level. We also discuss how these findings are situated within the broader engineering design and DfE landscape.

4.1 Certification analysis

To assess whether sustainability certifications align with user concerns, we analyzed user feedback and sentiment trends across certified products. Table 4 shows the positive sentiment ratio of reviews grouped by sustainability certification, with the bolded values indicating aspects that are directly relevant to a given sustainability certification based on its description.

These findings highlight the varying degrees of alignment between sustainability certifications and user perceptions. Certifications with well-defined sustainability claims tend to generate higher user approval. FSC-certified products received 88% positive sentiment for biodegradable materials, reinforcing user trust in its responsible sourcing claims. Blue Angel's energy renewability focus was validated with 93% positive sentiment, further strengthening its credibility in this domain. For product quality, BIFMA-certified products had the highest positive sentiment at 61%, indicating user recognition of durability and performance. In contrast, RCS100-certified products had only 25% positive sentiment for recyclability, suggesting that while users recognize the certification's intent, they may be less convinced of its effectiveness in practice.

FSC-certified products demonstrated the strongest alignment with their stated sustainability focus, particularly in biodegradable materials, which appeared in 5.02% of reviews. This was higher than all other certifications, where mentions of biodegradable materials were less than 1%. In contrast, RCS100, which emphasizes recycled content, had only 0.18% of reviews discussing recyclability. This low rate suggests that users may not strongly associate the certification with its intended focus, possibly due to less effective communication or visibility of its claims. It may also reflect a broader awareness gap, as many users may be unfamiliar with recycled-content certifications or the practical implications of these claims, rather than indicating a failure of the certification itself.

These differences highlight that user discussions align most strongly with certifications that emphasize tangible product attributes. This supports findings from [12, 35], which indicate that is important to incorporate features that are *perceived* as sustainable when engaging in sustainable design in order to best align with user needs and drive purchasing decisions.

Positive Sentiment Ratio				
Sustainability Aspect	**BIFMA**	**BA**	**FSC**	**RCS100**
Material: Bio Friendly	**8%**	**77%**	**88%**	17%
Material: Chemical Contents	0%	**36%**	36%	52%
Material: Recyclability	56%	**15%**	71%	**25%**
Material: Waste	**26%**	**21%**	28%	20%
Packaging	**38%**	**5%**	12%	41%
Environment: Bioenvironment	**0%**	**67%**	58%	17%
Environment: Climate	**100%**	**0%**	86%	88%
Energy: Consumption	**56%**	**51%**	32%	50%
Energy: Renewability	0%	**93%**	0%	0%
Manufacturing Process: Production	**11%**	**17%**	**8%**	0%
Manufacturing Process: Worker	**80%**	**73%**	100%	11%
Manufacturing Process: Supply	6%	**29%**	15%	20%
User Experience: Price	55%	42%	62%	72%
User Experience: Quality/ Performance	**61%**	55%	49%	57%
User Experience: Safety	**34%**	**20%**	26%	55%
General Sustainability	**20%**	**38%**	53%	24%

TABLE 4: POSITIVE SENTIMENT RATIO IN REVIEWS MENTIONING SUSTAINABILITY ASPECTS, GROUPED BY SUSTAINABILITY CERTIFICATION. BOLDED NUMBERS HIGHLIGHT ASPECTS THAT ARE EXPLICITLY RELEVANT TO EACH CERTIFICATION'S CRITERIA.

Importantly, our findings support the the critical role that sustainability labels and certifications play in advertising the sustainability of a product. Certifications that clearly communicated their sustainability attributes, like FSC's biodegradable materials and Blue Angel's energy efficiency, received higher positive sentiment scores, indicating stronger user recognition. In contrast, RCS100's lower score on recyclability suggested that users may struggle to connect recycled content claims with tangible benefits. These results suggest that improving user education on the practical advantages of recycled materials and making sustainability claims more transparent could strengthen their perceived value and effectiveness. This aligns with prior work showing that well-communicated sustainability claims can influence a user's decision-making process [36] and willingness to pay more for sustainability-certified products over conventional ones [37]. By improving the clarity and visibility of sustainability messaging, particularly for certifications with lower recognition, brands can better align with user expectations and strengthen the impact of sustainability labeling on purchasing behavior [38, 39].

4.2 Categorical Trends: Valued Features vs Areas of Improvement

This section examines sentiment analysis across various sustainability topics to explore insights from user reviews at scale, illustrating how sustainability aspects are prioritized by users across different product categories.

4.2.1 Topic Modeling-Driven Insights. Using LDA, we identified key topic areas of importance and then identified the relevant sustainability concerns unique to each product category. 18 LDA topics were identified as related to sustainability out of 200 total topics across our database. A list of a subset of topics that were generated and identified as sustainable can be seen in Table 5.

With the topic modeling approach, we identified that for home and kitchen products, users prioritize durability, energy efficiency, and sustainable materials, valuing long-lasting, reusable, and natural alternatives. In contrast, for office and electronics products, cost and maintenance concerns dominate, with frustration over disposable components like printer cartridges, signaling a need for longer-lasting, refillable, or recyclable options. Finally, reviews in appliances highlighted concerns over materials being used (like coffee filter paper processing) and product waste. These differences emphasize the importance of tailored sustainable redesign strategies that align with category-specific user expectations.

From these topics, specific design leads were generated by product category. For example, in appliances, discussions on coffee filters revealed a preference for unbleached, chemical-free options: one reviewer called them *"an excellent choice for coffee lovers who care about the environment."* Mentions of *"waste"* and *"box"* hinted at packaging issues, with another user stating, *"I only wish there were more in the box to make the packaging and shipping more worthwhile."* In electronics, the topic modeling result "printer hp toner cartridges buy new cartridge chip just bought" indicated frustration with frequent cartridge replacements, as one reviewer complained, *"Once again a printer with toner cartridges that cost more than the printer to replace...when you run out of ink, just buy a whole new printer."* Meanwhile, in home, kitchen, and tools, enthusiasm for solar-powered lights highlighted growing interest in energy efficiency, one user described such products as perfect for off-grid use, and the topic modeling result "easy great assemble box storage sturdy cushions store patio deck" underscored demands for durable, weather-resistant storage, as a reviewer praised the deck box for being *"quite sturdy"* and *"looking great"* on the patio.

Product Category	LDA topics categorized as sustainable (+ LLM reasoning)
Home & Kitchen + Tools	*1 - light good just don come lights like does solar need* *2 - box lid easy storage good product assemble boxes rain use easy great assemble box storage sturdy cushions store patio deck*
	Explanations: 1- The mention of solar-powered lights indicates a focus on energy-efficient, renewable energy solutions for home use. 2 - Durable storage boxes reduce the need for frequent replacements, minimizing plastic waste.
Appliances	*1 - coffee filters filter paper tiny pour money let bleached extra* *2 - perfect price box money product time delivered waste item aromaboy*
	Explanations: 1- Mentions of "bleached" and "extra" could indicate concerns about filter processing methods (e.g., chlorine-bleached vs. unbleached filters). Some consumers prefer unbleached filters for environmental reasons due to reduced chemical use. 2 - The presence of words like "waste" and "box" suggests discussions about packaging waste, sustainability concerns regarding delivery, or excessive material usage in the product.
Electronics	*printer hp toner cartridges buy new cartridge chip just bought*
	Explanation: Toner and cartridge consumption, frequent cartridge replacements raise concerns about waste generation and recyclability.

TABLE 5: LDA TOPICS IDENTIFIED AS HAVING SUSTAINABLE THEMES, GROUPED BY PRODUCT CATEGORY, ALONG WITH THE LLM'S REASONING FOR CLASSIFYING THEM AS SUSTAINABLE.

These findings highlight how sustainability priorities vary across product categories. However, a limitation exists that the outputs need to be manually filtered to separate sustainability-related items from general ones. To address this, we adopt an ABSA-driven approach in the next section.

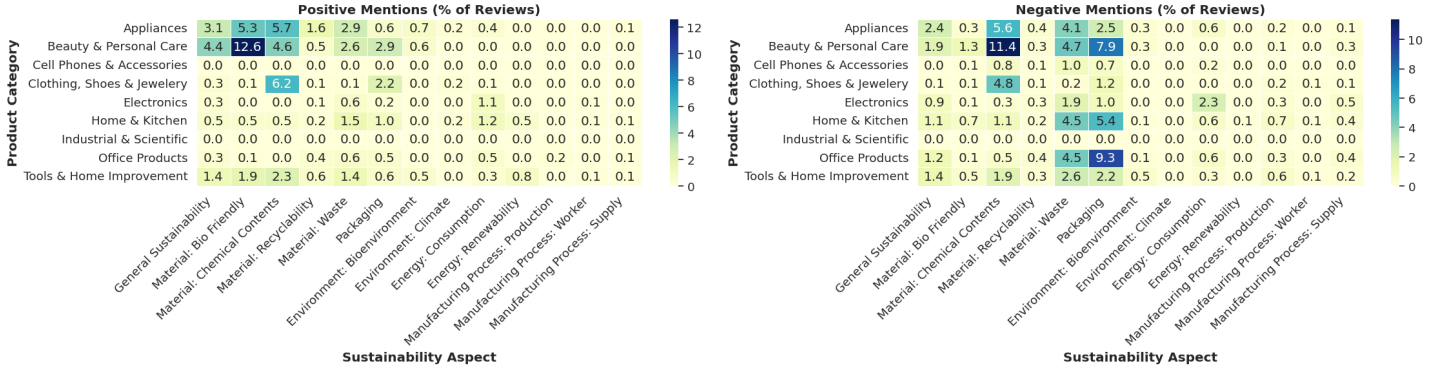

FIGURE 2: HEATMAPS SHOWING POSITIVE (LEFT) AND NEGATIVE (RIGHT) MENTIONS OF SUSTAINABILITY ASPECTS ACROSS PRODUCT CATEGORIES, NORMALIZED PER PRODUCT CATEGORY.

4.2.2 ABSA-Driven Insights. The second analysis approach involved using peaks in ABSA-related sentiment trends to group inputs for the LLM prompt. This method allows for targeted insights by selecting reviews where sentiment intensity is highest, ensuring that both positive and negative user experiences are effectively captured.

Figure 2 shows the distributions of sentiment analysis scores across different sustainability topics for each product category. Notably, user experience-related topics are excluded from this visualization due to their disproportionately high counts, which would otherwise distort the representation of the data. These categories, which include reviews mentioning price, quality, and safety, were excluded due to their generality and limited relevance to environmental sustainability. However, we acknowledge that this also removed relevant content on durability, which future versions of the dictionary will aim to capture more precisely. High frequency categories may indicate areas of high importance for the users and thus actionable areas for designers to address. Categories with large numbers of negative reviews may indicate areas where there is room for improvement while categories with large numbers of positive reviews may indicate valued features in the product that should aim to be maintained.

Beauty & personal care saw strongly polarizing reviews, with peaks in both positive and negative reviews surrounding topics of materials and packaging. This is similar to reviews in *clothing, shoes, and jewelry*, showing a trend in products that are typically worn and thus have material safety concerns. *Home & kitchen*, *office products*, and *electronics* saw much higher negative reviews than positive ones, highlighting areas of customer dissatisfaction among sustainability reviews. Energy-related sentiments were highest among *electronics* and *home & kitchen* categories, appropriately, given these categories contained most of the electric-powered products.

Sustainability aspects related to manufacturing processes were the least mentioned among sustainability topics, reinforcing the idea that users view sustainability primarily through the lens of personal use, rather than through technical or climate-driven perspectives [11]. Similarly, reviews relating to material waste and packaging saw the most mentions among reviews, highlighting a sustainability aspect that is more tangible and directly related to how users interact with the products.

These trends highlight the different sustainability priorities across product categories, and these priorities can be used to guide prompting for sustainability insights from LLMs. For example, within *clothing, shoes, and jewelry*, users are primarily concerned with the chemical composition of materials, indicating where sustainable design efforts could align with user needs. To explore this further, analyzing positive reviews helped identify product features that are valued and should be maintained. These reviews were provided to an LLM to synthesize a list of desirable product attributes:

- **Hypoallergenic properties**: *"Not only are these earrings super cute, but they're actually hypoallergenic as advertised!" "These are the first earrings I've worn in ages that don't leave my lobes feeling irritated to the point of pain. I actually forget I'm wearing them, they're so comfortable.* I get to enjoy wearing jewelry again."
- **Non-tarnishing**: *"I bought these in silver as well and wore them for a month on vacation nonstop in super hot, humid weather, in the pool, ocean, and shower. They are still in great shape. No tarnish, no discoloration, no irritation." "I have super sensitive ears and a nickel allergy, and these didn't give me any trouble at all."*
- **Comfort**: *"They are lightweight and perfect for people who want to wear trendy hoops without worrying about an allergic reaction."*

In contrast, sustainability concerns in *electronics* often revolved around material waste, packaging, and energy consumption, with issues spanning multiple product types. Key concerns included poor shipping practices, lack of essential accessories, inefficient toner use, and suboptimal starter ink cartridges. These concerns are reflected in the reviews and can be used to identify of areas for improvement:

- **Poor shipping practices**: *"I'd have given it 5 stars, but rather than being packaged in a shipping box with protective materials, the keyboard was shipped in its original*

box with a UPS label applied and could have been easily damaged during shipment."

- **Inefficient toner use**: *"The toner 414A black it came with is supposed to yield 2400 pages... I only got 600ish out of it."*
- **Suboptimal starter ink cartridges**: *"Although the Q&A indicate it comes with a full toner cartridge, it comes only with a cartridge marked 'introductory.' "Toner ran out in no more than 200 pages printed, leading to unnecessary consumption and waste of."*

These reviews reveal critical opportunities for improving sustainability in electronics, particularly in packaging, accessory inclusion, and resource efficiency, which can guide design improvements.

Extracting these specific user insights enables designers to focus their sustainable design efforts effectively, leveraging them in a variety of ways. For example, Cor and Zwolinski proposed a protocol that emphasizes understanding user interactions and behaviors to enhance the environmental performance of user products. This method involves mapping user behaviors and profiles to various Design for Sustainable Behavior (DfSB) strategies, allowing designers to tailor products that encourage sustainable usage patterns [40]. By applying this protocol, designers could gain targeted insights into user preferences, such as identifying features that users value, like durability or energy efficiency, from positive reviews. On the other hand, examining negative feedback helps reveal areas for improvement, such as material degradation or poor usability, guiding design modifications. This dual approach ensures that both favorable and critical feedback are considered, leading to more informed, user-centered decisions that align with sustainability goals and user expectations. These insights also support several goals outlined for future sustainable design methods and tools [4], including accessibility for non-experts, data-driven approaches, task-specific focus, cost-effectiveness, and the integration of environmental factors to provide concrete, actionable design recommendations.

Overall, these findings illustrate how sustainability concerns vary across product categories, with some industries prioritizing material safety while others focus on waste reduction and packaging efficiency. Not only do we see how users' sustainability priorities differ across products, but the novel capabilities of LLMs allow us to identify key product areas and features that should either be sustained (valued features) or re-designed (areas of improvement) within a diverse database. The database highlights how users tend to focus on tangible, personal-use aspects of sustainability, such as packaging and waste reduction, while overlooking more technical concerns like manufacturing processes. This section demonstrates that by using ABSA trends to structure LLM prompts, sustainability-related insights can be extracted in a targeted and actionable manner.

5. CASE STUDY: GENERATING PRODUCT-LEVEL SUSTAINABLE DESIGN LEADS

To showcase the utility of this type of database, this case study explores how deeper, product-specific insights can be derived from it. Specifically, the process of how identifying sustainable design leads from user reviews could be automated is examined. Three products were analyzed: an HP OfficeJet Pro printer, an HP Chromebook laptop, and a USB-C to HDMI Cable. All products were certified as Climate Pledge Friendly and were chosen based on prior work that involved manually deriving insights for them [11]. Data for these products was extracted following the process outlined above.

To generate insights, the ABSA-driven approach was used, where peaks in ABSA trends were identified, and reviews from these categories were analyzed by an LLM and prompted to produce actionable design leads. Notably, for this product-specific approach, the products' features were inputted to the LLM model as well to provide additional context on components that could be addressed.

5.1 Case Study: Identification of sustainable design leads

A full summary of the sustainable design leads generated are presented in the appendix (Appendix D). The LLM-generated design leads are each supported by specific reviews, ensuring that user feedback is driving the suggestions that are presented.

The HP Officejet Pro printer was the first product example, whose reviews' ABSA scores appear in Figure 3, showed large peaks in negative sentiments in the material waste and energy consumption categories. Reviews from these categories were used as inputs to the LLM, which provided the following sustainable design leads, with the full list of generated sustainable design leads available at Appendix D. Most of the design suggestions that were manually derived in prior work appeared in the LLM-generated leads. For example, manual analysis of the printer reviews suggested that **a metallic (steel or aluminum) tray can be used to replace the sensitive plastic parts**. Similarly, the LLM recommended to **improve durability and sturdiness of design components by reinforcing key parts of the printer, like the paper tray and cartridge cover, to prevent breakage in regular use.** To justify this lead, it pointed to the following reviews: *"Everything is plastic which means flimsy... built to be cheap enough to hit a price point such that quality is compromised." "The paper tray is impossible to adjust for different paper sizes and envelopes."*.

Similarly, we compare sustainable design leads for an HP Chromebook laptop. ABSA scores showed peaks in negative packaging, and positive/negative energy consumption categories. Reviews from these categories produced a variety of suggestions, which encompassed the manually derived insights. For example, one of the LLM-generated solutions suggested to **enhance robustness through sustainable design by investigating durable and sustainable materials that can help enhance the robustness of the body's design without increasing weight.**. This was justified by providing relevant reviews: *"You get what you pay for. So for the price I love that it's lightweight meaning easy to carry around.", "Lesson learned, I ordered a protective hard case."*

Finally, the last product compared was a USB-C to HDMI cable. For the cable, ABSA scores in negative material waste and positive/negative packaging reviews. Generated insights encompassed half of the manual insights. Notably, the most specific

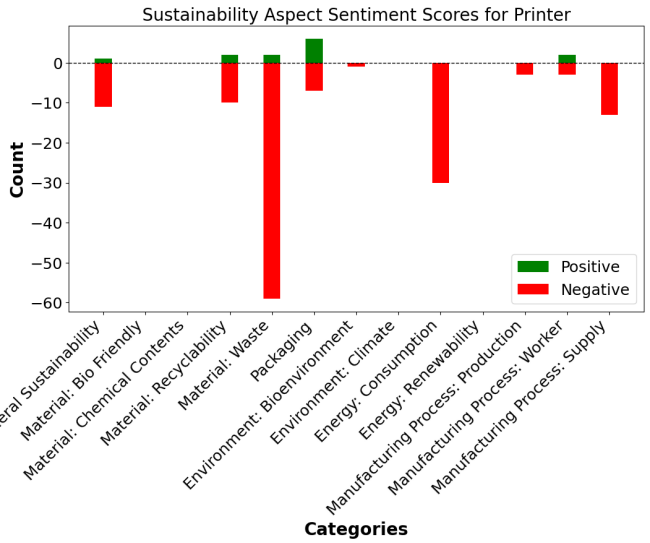

FIGURE 3: ABSA SCORES FROM HP OFFICEJET PRO PRINTER REVIEWS. LARGE NEGATIVE SENTIMENTS APPEAR IN THE MATERIAL WASTE AND ENERGY CONSUMPTION CATEGORIES.

design leads suggested during the manual process (**Design 'flex points' to allow the cable to be bent without altering the joints** and **Aluminum alloy casing is a valued material choice due to its heat dissipation capabilities.**), were not suggested by the LLM. This could be due to a variety of reasons, including the fact that the reviews being used are not necessarily the exact same set due to random sampling. Nevertheless, there was a variety of LLM-generated design leads, which did have conceptual overlap with the manually-derived ones. For example, a valued feature of the product appeared to be its durability, as evidenced by both manual analysis and the LLM-generated lead: **Maintain high-quality materials by continuing to use durable, high-quality materials for the product and accessories like cords**.

These comparisons highlight the capability of LLMs to generate sustainable design leads by identifying and justifying solutions based on user feedback, demonstrating their potential to integrate user-driven insights into sustainability-focused product improvements.

5.2 Comparison with manual methods

Overall, the case study demonstrates that identifying product-specific design leads is not only feasible but also produces results comparable to the manually-derived insights. The LLM is capable of generating more insights in a time-efficient manner, as shown in Appendix D, and can ground its suggestions in user reviews when prompted appropriately. However, there are instances where manually derived leads are more specific in their recommendations or the features they identify. For instance, manual analysis of the printer reviews suggested using steel or aluminum for a more durable tray material. In contrast, the LLM's recommendation was broader, suggesting improvements to the durability and reinforcement of the paper tray to prevent breakage during regular use. While this could be refined with additional prompting, it illustrates a trade-off in the method. Although manual insights may yield fewer but highly specific leads, the LLM approach can generate a larger volume of potential leads, offering a broader spectrum of design possibilities.

6. FUTURE WORK

While promising, our approach was constrained by the availability of reviews for each product on Amazon, and a bias for making for more recent reviews available. This limitation may impact the comprehensiveness of the insights generated, as older reviews might offer valuable, yet underrepresented, perspectives on sustainability concerns. In addition, variations in certification requirements may influence user perception and trust, and future work should explore how the stringency of these requirements impacts user judgment.

Future work should refine the sustainability aspect dictionary to better capture relevant yet currently underrepresented themes, such as durability, which were inadvertently excluded in the current approach. In addition, future research could explore integrating user feedback with life cycle assessment data using knowledge graphs to bridge the gap between user perception and ecological reality. In parallel, combining this database with agentic modeling techniques could facilitate the creation of data-informed personas in future design research, supporting the establishment of sustainability oriented personas ground in realistic feedback [41]. Finally, as vision models become more prevalent in design work, this research could extend to multimodal analysis, where user reviews are enriched with visual data. Computer vision could help assess product review images for wear, material degradation, or repairability, validating sustainability concerns mentioned in text.

This work centered on identifying insights centered around environmental sustainability, but the approach can naturally extend to other pillars of sustainability (social and economic) by modifying the aspects and prompting used. Doing so could provide an accessible and scalable way to analyze how users are interacting with these topics, if at all. As themes of ethics, equity, and justice in engineering design continue to gain prominence, and the field seeks to equip designers with tools to address these issues [42, 43], our approach could provide a valuable lens for: 1) amplifying user voices that are often hard to reach, 2) understanding the impact of products on users, or 3) tracking social, ethical, or economic trends over time.

Finally, as emerging technologies are applied to sustainable design research, it is crucial to assess the environmental impact of the technologies themselves. The training and development of many language models incur massive carbon footprints [44–46]. Though these technologies will continue to get more efficient, there is a need to develop better calculators for measuring AI-related emissions, allowing this kind of research to be better-informed of its own impact.

7. CONCLUSION

This work presents the development of a database of online product reviews, alongside the application of various sustainability-oriented analysis techniques. These methods, enabled by advancements in large language models, reveal new ways to extract sustainability insights from user feedback. Analyzing

over 23,000 Amazon reviews across 290 consumer products, we demonstrate a new, scalable approach to surfacing sustainability-related design and communication opportunities directly from user feedback. Unlike traditional methods, which often require manual effort and domain expertise, our approach automates the identification of product-specific concerns and valued features, offering an efficient and accessible tool for sustainable design practice.

Our findings reveal that certifications emphasizing tangible, experience-based product attributes are more likely to resonate with users, while attributes related to upstream processes, like manufacturing, are often overlooked, highlighting communication gaps in how sustainability is conveyed. A case study is also presented to demonstrate how this approach generates product-specific sustainable design leads for a printer, laptop, and cable that are comparable to manually-derived leads. By capturing user-centric perspectives at scale, this work offers a new way to bridge the gap between sustainability performance and user perception, supporting both design iteration and strategic sustainability communication.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. 2146752 as well as an Amazon Research Award Fall 2023. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not reflect the views of the National Science Foundation or Amazon.

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APPENDIX A. SUSTAINABILITY ASPECT DICTIONARY

Aspect	Definition
General Sustainability	Overall perception of the product's commitment to sustainability.
Material: Bio-Friendly	Use of environmentally friendly materials, such as biodegradable or naturally sourced components.
Material: Chemical Contents	Presence or absence of harmful chemicals in the product.
Material: Recyclability	Ease with which the product materials can be recycled.
Material: Waste	The product's ability to reduce waste during its lifecycle.
Packaging	Sustainability of product packaging, including recyclability and minimal use of non-recyclable materials.
Environment: Bioenvironment	Impact of the product on natural ecosystems and wildlife.
Environment: Climate	The product's effect on climate change, including its carbon footprint.
Energy: Consumption	Efficiency of the product's energy use during operation.
Energy: Renewability	Use or promotion of renewable energy sources in the product's lifecycle.
Manufacturing Process: Production	Sustainability of the production process, including material usage and energy efficiency.
Manufacturing Process: Worker	Ethical labor practices and worker conditions in the product's manufacturing.
Manufacturing Process: Supply Chain	Sustainability of the supply chain, including material sourcing and transportation.
User Experience: Price	Affordability and perceived value for money.
User Experience: Quality/Performance	Product quality, durability, and overall performance.
User Experience: Safety	Safety of the product during use.

TABLE 6: SUSTAINABILITY ASPECTS AND DEFINITIONS USED FOR ASPECT-BASED SENTIMENT ANALYSIS DURING DATASET CURATION.

APPENDIX B. ASPECT-BASED SENTIMENT ANALYSIS PROMPT

```
Given the customer comment "{comment}" about the
    product "{product_name}", analyze the sentiment of
     the comment across the following sustainability
    dimensions and update the corresponding rating in
    the provided JSON format. Use the following
    guidelines for assigning sentiment ratings:

Positive Sentiment: Assign a value of 1 if the comment
     expresses positive sentiment about the aspect.
Negative Sentiment: Assign a value of -1 if the
    comment expresses negative sentiment about the
    aspect.
Neutral or No Mention: Assign a value of 0 if the
    comment is neutral about the aspect or does not
    mention it.

Definitions of Dimensions: "{Sustainability␣aspect␣
    definitions"

Output:
Using chain-of-thought reasoning, analyze the
    sentiment step-by-step for each dimension and
    ensure consistency in ratings. After your analysis
    , output only the JSON in the following format
    with nothing else:
{json.dumps(expected_structure, indent=2)}
```

Prompt 1: Prompt used to perform aspect-based sentiment analysis on user reviews.

APPENDIX C. SUSTAINABLE DESIGN LEADS PROMPT

```
You are a sustainability expert analyzing a set of
    user feedback about the product "{product_name}".
    Given the following reviews, extract sustainable
    design insights based on common themes across the
    feedback.

Take into account the specific users' needs and
    preferences. For every design lead, write an
    explanation connecting it to specific wording in
    the review that explains the reasoning behind the
    insight.

Follow a chain of thought reasoning process:
1. Identify key themes across the reviews: what are
    the most common positive or negative mentions?
2. Look for recurring feedback on sustainability
    aspects.
3. Determine actionable design leads: Is there room
    for improvement in the product based on the
    feedback?
4. Justify each lead by referencing specific phrases
    or words from the reviews.

Positive reviews should highlight areas that users are
     happy with and should be maintained. Negative
    reviews indicate areas where improvements could be
     made to make the product more sustainable.

Return insights in the following format, without extra
     words, explanations, or formatting: Insight - (
    insight given), Suggestion - (specific design
    suggestion), Reason - (direct explanation from
    review. Include multiple reviews if they are
    relevant).

Focus on producing insights that are very focused on
    these specific features of the product. They
    should be detailed and actionable for designers.

User Reviews: "{reviews}"
```

Prompt 2: Prompt used to generate sustainable design leads from existing user reviews.

APPENDIX D. CASE STUDY RESULTS

Product	Manually-derived Design Leads	LLM-generated design leads
Printer	**Metallic (steel or aluminum) tray** can be used to **replace the sensitive plastic parts.** The "print both sides" feature is important because **low ink consumption is highly valued.** A modular printer could be valued given the difficulty and cost of replacing parts. Several complaints related to **installation** and **printing speed** appeared.	**Improve durability and sturdiness** of design components by **reinforcing key parts of the printer, like the paper tray and cartridge cover,** to prevent breakage in regular use. **Improve ink usage efficiency** and provide better ink solutions for low-volume users by developing ink cartridges with a more extended shelf life and offering smaller, more affordable options. **Evaluate and enhance print speed** and overall efficiency by implementing engineering solutions or providing clearer user settings to reduce warm-up and maintenance times. Address setup and connectivity issues to enhance the initial user experience by **simplifying setup instructions** and including a direct USB option or better wireless connectivity support documentation. Consider reducing software dependencies and eliminating unnecessary promotional features by redesigning the printer's software to function without mandatory login requirements and minimizing promotional notifications. Expand non-spyware functionalities for users by offering privacy-centered software or a more transparent user agreement to assure customers about data handling practices.
Laptop	**Duration and battery lifetime are key sustainability features.** **Thin and lightweight designs** are highlight appreciated. However, **this could lead to fragility, so adding reinforcements to specific elements would help** support duable and sustainable laptops.	**Improve battery sustainability** by exploring options for using more sustainable materials in battery production to maintain or improve long battery life. **Maintain a lightweight and user-friendly design** by ensuring future models maintain or improve the lightweight feature and usability. **Enhance robustness through sustainable design by investigating durable and sustainable materials that can help enhance the robustness of the body's design without increasing weight.** Expand repairability visibility by considering making repairability a selling feature, possibly through offering spare parts or highlighting ease of repair to extend the product's lifecycle sustainably. Maintain quick and easy setup by continuing to streamline setup processes while considering recyclable or less resource-intensive packaging. Improve packaging sustainability by implementing eco-friendly, protective packaging made from recycled materials. Ensure the product comes with proper documentation by including a digital or recycled paper instruction manual and package slip with each product.
Cable	**Braided nylon solutions are durable and valued** by customers. Design 'flex points' to allow the cable to be bent without altering the joints. Aluminum alloy casing is a valued material choice due to its heat dissipation capabilities. Even low-rated reviews praised durability but **criticized connectivity or degraded image quality**.	**Maintain high-quality materials by continuing to use durable, high-quality materials** for the product and accessories like cords. Improve packaging durability by using sturdier, weather-resistant packaging materials. **Increase resolution capability** by upgrading cable capability to support higher resolutions and refresh rates. Improve product odor by investigating and mitigating odorous materials or processes in manufacturing. Maintain affordable pricing with eco-conscious incentives by considering incentives for sustainable returns or recycling schemes at the current price points. Improve compatibility with a wider range of devices by enhancing the product's connectivity capabilities to ensure seamless operation with various systems, specifically targeting compatibility with different MacBook models.

FIGURE 4: RESULTS OF OUR CASE STUDY COMPARING MANUALLY-DERIVED SUSTAINABLE DESIGN LEADS AGAINST LLM-GENERATED ONES. BOLDED TEXT INDICATES INSIGHTS THAT APPEAR IN BOTH COLUMNS FOR A GIVEN PRODUCT.