EcoTrace: A Modular Framework for Product Sustainability Transparency Using AI-Assisted Evaluation and QR-Based Traceability

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***Abstract*—** Ensuring transparency in product sustainability has become a critical challenge due to increasing environmental concerns and the growing demand for responsible consumption. Existing sustainability communication mechanisms largely rely on static eco-labels, certifications, and manufacturer-declared claims, which often lack detailed traceability and are difficult for consumers to verify [1]. Although supply chain traceability systems have been widely explored to improve accountability and product lifecycle visibility, many of these systems are designed primarily for internal monitoring rather than consumer-facing transparency platforms [2].

This research proposes EcoTrace, a modular and scalable framework aimed at improving product sustainability transparency through structured traceability and AI-assisted evaluation. The framework introduces a layered architecture that separates product definition, batch lifecycle tracking, sustainability assessment, verification, and public transparency. A decision-based evaluation mechanism determines when sustainability reassessment is required, thereby reducing redundant analysis and improving system efficiency.

AI-assisted sustainability scoring generates interpretable indicators that help communicate environmental impact information in a structured and understandable manner. The framework also supports optional third-party verification mechanisms to enhance credibility and trust. To enable real-time consumer access, physical products are linked to digital transparency records through QR-based access mechanisms, allowing users to retrieve sustainability information for specific product batches.

The proposed framework is validated through a prototype-based qualitative evaluation focusing on architectural feasibility, modularity, and transparency effectiveness. The results indicate that EcoTrace provides a practical and extensible foundation for developing digital systems that promote sustainability transparency and informed consumer decision-making.

***Keywords*—** *sustainability transparency, product traceability, AI assisted evaluation, QR based access, sustainable consumption*

I. INTRODUCTION

Environmental sustainability has become an increasingly critical global concern due to rising resource consumption, industrial expansion, and climate-related challenges. Governments, organizations, and consumers are increasingly demanding greater transparency regarding the environmental and social impacts of products throughout their lifecycle. Sustainable consumption practices require access to reliable information about product sourcing, manufacturing processes, and environmental impact in order to support informed purchasing decisions [8].

Currently, sustainability information is commonly communicated through eco-labels, certifications, and manufacturer-declared claims. While these mechanisms aim to encourage responsible consumption, they often provide limited transparency and are difficult for consumers to interpret. In many cases, sustainability claims cannot be easily verified by consumers, which reduces trust and limits the effectiveness of sustainability communication mechanisms [1], [7]. Furthermore, traditional labeling systems are largely static and fail to provide detailed lifecycle information about products.

Supply chain traceability systems have been widely studied as a potential solution to improve transparency in product lifecycles. Traceability technologies enable tracking of products and materials across different stages of production and distribution, thereby improving accountability, quality control, and safety management within supply chains [1], [2]. However, many existing traceability systems are designed primarily for internal operational monitoring or regulatory compliance rather than consumer-facing transparency. As a result, the benefits of traceability technologies are often not directly accessible to end consumers.

Recent advancements in digital technologies provide new opportunities to improve product transparency. Quick Response (QR) codes allow physical products to be linked to digital information systems, enabling consumers to access product-related data quickly using mobile devices. Such technologies offer a scalable and cost-effective mechanism for delivering product information at the point of purchase.

However, most QR-based systems primarily provide static product descriptions or marketing content rather than structured sustainability information.

At the same time, artificial intelligence techniques have shown potential in analyzing sustainability-related data and generating structured evaluations of environmental impact. Explainable artificial intelligence approaches further enable AI systems to provide interpretable insights, improving transparency and trust in automated decision-making systems [5], [6]. Despite these advancements, existing systems rarely integrate traceability mechanisms, sustainability evaluation models, and consumer-accessible transparency platforms into a unified framework.

To address these challenges, this paper proposes EcoTrace, a modular framework designed to improve product sustainability transparency through structured traceability and AI-assisted evaluation. The proposed framework integrates batch-level traceability, decision-based sustainability assessment, and QR-based consumer access within a unified architecture. By emphasizing modularity, scalability, and interpretability, EcoTrace aims to provide a practical foundation for digital systems that promote sustainability transparency and responsible consumption.

The remainder of this paper is organized as follows. Section II reviews existing research on traceability systems, sustainability evaluation approaches, and QR-based transparency mechanisms. Section III describes the problem definition and identifies the research gap addressed by this work. Section IV presents the proposed EcoTrace framework. Section V explains the sustainability evaluation methodology. Section VI describes the prototype implementation and qualitative evaluation. Section VII discusses the implications and limitations of the framework, and Section VIII concludes the paper with future research directions.

II. RELATED WORK

Research on sustainability transparency and product traceability has gained significant attention in recent years due to increasing environmental concerns and the need for responsible production and consumption practices. Existing studies in this domain generally focus on four major areas: supply chain traceability systems, sustainability evaluation methods, QR-based information access mechanisms, and consumer trust in transparency platforms.

Supply chain traceability systems are widely studied as a method for improving product lifecycle visibility and accountability. Traceability enables organizations to track products and materials across various stages of production, processing, and distribution. Such systems play an important role in ensuring product safety, quality control, and regulatory compliance within supply chains. For example, Aung and Chang [1] highlight how traceability mechanisms can significantly improve food safety and supply chain transparency. Similarly, Badia-Melis et al. [2] provide a comprehensive review of modern traceability technologies and discuss the adoption of digital tracking methods in supply chain management.

Sustainability-oriented supply chain research has also explored frameworks for integrating environmental considerations into production and distribution systems. Sustainable supply chain management aims to balance economic performance with environmental and social responsibility. Several studies emphasize the importance of reliable data collection and transparency mechanisms in achieving sustainability objectives. For instance, Choi and Luo [3] discuss how data quality and digital information systems influence sustainability management within global supply chains. In addition, research on sustainable supply chain practices highlights the need for improved data accessibility and transparency for both organizations and consumers [4].

Another emerging area of research involves the use of artificial intelligence techniques to analyze sustainability-related information. AI-based systems can process large volumes of environmental and operational data to generate sustainability insights and predictive assessments. However, the interpretability of such systems is an important concern, particularly when AI outputs are used in decision-making contexts. Explainable artificial intelligence approaches aim to address this challenge by providing transparent reasoning behind algorithmic outputs, thereby improving trust and usability of AI-driven systems [5], [6].

Consumer trust is another critical factor influencing the effectiveness of sustainability transparency initiatives. Studies show that traceability and accessible product information can significantly improve consumer confidence and perceived product reliability. For example, research on organic food supply chains demonstrates that transparent traceability systems enhance consumer trust and influence purchasing decisions [7]. Despite these advancements, many existing systems still provide limited direct access to detailed sustainability data for consumers.

Overall, existing literature highlights the importance of traceability, sustainability evaluation, AI-based analysis, and transparency in supply chains. However, most studies address these aspects independently rather than integrating them into a unified consumer-facing system. This fragmentation creates a gap in current research, motivating the development of integrated frameworks that combine traceability, sustainability evaluation, verification mechanisms, and real-time information access. The EcoTrace framework proposed in this paper aims to address this gap by providing a modular system that unifies these components within a single transparency-oriented architecture.

III. PROBLEM DEFINITION AND RESEARCH GAP

Despite the increasing global emphasis on sustainable production and responsible consumption, consumers still face significant challenges in accessing reliable and transparent sustainability information at the product level. Sustainability claims are commonly communicated through eco-labels, certifications, and manufacturer-provided declarations. Although these mechanisms aim to promote environmentally responsible purchasing behavior, they often provide limited information about the underlying sourcing, manufacturing processes, and environmental impact of products. Furthermore, such claims are typically difficult for consumers to independently verify, which can reduce trust and limit informed decision-making [1], [7].

Supply chain traceability systems have been proposed as a solution for improving visibility across product lifecycles. These systems enable organizations to monitor product movement and track materials throughout production and distribution processes. Research has shown that traceability systems can enhance quality assurance, improve supply chain accountability, and support regulatory compliance [1], [2]. However, many existing implementations are designed primarily for internal operational management rather than consumer-facing transparency. As a result, the information generated by traceability systems is rarely accessible to end users at the point of purchase.

In addition to traceability systems, sustainability assessment frameworks have been developed to evaluate environmental and social impacts within supply chains. These frameworks typically rely on structured data analysis, audits, or environmental indicators to measure sustainability performance. While such approaches contribute to sustainability monitoring, they often operate independently of traceability systems and lack direct integration with consumer-accessible information platforms [3], [4]. This separation limits the effectiveness of sustainability communication and prevents consumers from fully understanding the lifecycle impact of products.

Recent technological advancements have introduced digital solutions such as QR-based product information systems and AI-assisted evaluation methods. QR codes provide an efficient mechanism for linking physical products to digital records, allowing consumers to access additional product information using mobile devices. At the same time, artificial intelligence techniques can analyze sustainability-related data and generate structured evaluations of environmental impact. However, many existing systems implement these technologies independently, without integrating traceability data, sustainability evaluation, and consumer transparency into a unified framework [5], [6].

Based on these observations, the key research gap lies in the absence of an integrated and modular framework that combines product traceability, sustainability evaluation, verification mechanisms, and real-time consumer transparency. Existing systems typically address only individual components of this problem, resulting in fragmented solutions that fail to provide comprehensive sustainability visibility.

To address this gap, this research proposes the EcoTrace framework, which integrates batch-level traceability, decision-based sustainability evaluation, AI-assisted scoring, and QR-based transparency within a unified architecture. By connecting these components into a structured system, EcoTrace aims to provide scalable and interpretable sustainability transparency that is accessible directly to consumers.

IV. PROPOSED ECOTRACE FRAMEWORK

This section presents the proposed EcoTrace framework, which aims to address the identified research gap by providing an integrated and modular approach to product sustainability transparency. The framework combines product traceability, sustainability evaluation, verification mechanisms, and consumer-level transparency within a unified architecture. Previous research has highlighted the importance of traceability systems in improving supply chain visibility and accountability [1], [2], while sustainable supply chain studies emphasize the need for digital transparency mechanisms to support environmental monitoring and responsible production practices [3], [4]. EcoTrace builds upon these concepts by integrating traceability, evaluation, and consumer transparency within a single modular framework.

EcoTrace follows a modular architecture, where system responsibilities are divided into independent but interconnected components. This design improves scalability, flexibility, and maintainability, allowing the system to evolve without requiring significant structural modifications.

A. Product Definition Layer

The first component of the EcoTrace framework is the product definition layer, which establishes the foundational representation of products within the system. At this level, products are defined conceptually with attributes such as product category, material composition, packaging characteristics, and sustainability-related metadata.

Separating product definitions from manufacturing instances enables the system to maintain consistent product-level information while supporting variations across different production cycles. This abstraction ensures that sustainability attributes can be managed efficiently across multiple product batches.

B. Batch Lifecycle Tracking

EcoTrace introduces batch-level traceability as a core design element. Instead of treating products as static entities, the framework tracks individual manufacturing batches as dynamic units within the system. Each batch represents a specific production instance and may contain variations in materials, sourcing conditions, transportation methods, or manufacturing parameters.

Traceability mechanisms are widely recognized for improving supply chain transparency and accountability [1], [2]. By capturing lifecycle information at the batch level, EcoTrace provides a more accurate representation of sustainability characteristics associated with real-world production processes.

C. Sustainability Evaluation Module

The sustainability evaluation module is responsible for assessing the environmental impact associated with each product batch. The module processes sustainability-related attributes and generates structured sustainability indicators that reflect environmental performance.

EcoTrace incorporates AI-assisted analysis to support sustainability evaluation. Artificial intelligence techniques have increasingly been applied to analyze complex datasets and generate sustainability insights. Explainable AI approaches further improve transparency by providing interpretable outputs that help users understand the reasoning behind evaluation results [5], [6].

D. Verification and Validation Module

To enhance trust in sustainability claims, EcoTrace supports integration of third-party verification mechanisms. External validation inputs such as certification documents, laboratory testing reports, or regulatory compliance records can be associated with specific product batches.

This hybrid approach combines automated sustainability evaluation with independent verification processes. While AI-assisted analysis improves scalability, external verification enhances credibility and reliability in contexts where higher levels of assurance are required.

E. Consumer Transparency Interface

The final component of the EcoTrace framework is the consumer transparency interface, which provides public access to sustainability information. EcoTrace links physical products to digital transparency records using QR-based access mechanisms.

Each product batch is associated with a unique QR code that directs users to its digital sustainability record. When scanned using a mobile device, the QR code provides consumers with detailed information about the product batch, including sustainability indicators, production attributes, and verification status. Research has shown that improved transparency and traceability mechanisms can significantly increase consumer trust in product information systems [7].

F. Framework Integration

The EcoTrace framework integrates these modules into a cohesive system that supports sustainability transparency across the product lifecycle. The product definition layer provides a structured representation of products, while batch lifecycle tracking captures production-specific variations. The sustainability evaluation module analyzes environmental attributes, and the verification module supports independent validation. Finally, the consumer transparency interface enables public access to sustainability information through QR-based mechanisms.

By combining these components within a modular architecture, EcoTrace provides a scalable and extensible foundation for sustainability transparency systems that connect supply chain data, analytical evaluation, and consumer accessibility.

V. SUSTAINABILITY EVALUATION METHODOLOGY

The sustainability evaluation methodology in EcoTrace provides a structured mechanism for assessing sustainability characteristics at the batch level. Unlike traditional static labeling approaches, the proposed methodology integrates traceability data, decision-based reassessment logic, and AI-assisted analysis to generate sustainability indicators. The objective is to ensure transparency while maintaining scalability and computational efficiency.

A. Evaluation Unit Definition

EcoTrace defines the production batch as the primary unit of sustainability evaluation. Sustainability characteristics may vary across different manufacturing cycles due to variations in raw materials, sourcing locations, transportation methods, and production parameters.

By focusing evaluation at the batch level rather than the product level, the framework captures real-world variability more accurately and enables more detailed sustainability representation.

B. Attribute Monitoring and Change Detection

The evaluation process begins with monitoring sustainability-related attributes associated with each batch. These attributes may include material composition, sourcing origin, production energy consumption, logistics parameters, and packaging characteristics.

A change detection mechanism compares the attributes of the current batch with previously evaluated configurations. If no significant variation is detected, previously computed sustainability indicators may be reused. If substantial differences are identified, the system triggers a new sustainability evaluation process. Monitoring lifecycle attributes in this manner is a common approach in modern traceability systems designed to improve transparency and supply chain accountability [1], [2].

C. AI Assisted Sustainability Assessment

When reassessment is required, EcoTrace applies AI-assisted analytical models to evaluate sustainability-related inputs. These models analyze production attributes and generate sustainability indicators that represent potential environmental impacts.

To maintain transparency, the framework emphasizes explainable AI techniques. Explainable AI methods enable automated systems to provide interpretable insights into decision-making processes, improving trust and usability in sustainability evaluation systems [5], [6].

D. Hybrid Verification Integration

Recognizing that automated assessment alone may not satisfy high assurance requirements, the methodology supports integration of external verification mechanisms. Third party validation inputs, such as laboratory assessments or certification confirmations, can be incorporated into the sustainability record of a batch.

This hybrid evaluation structure allows the framework to balance automation with credibility. Automated AI assisted evaluation provides scalability, while external verification enhances reliability in regulated or sensitive domains.

E. Methodological Properties

The proposed sustainability evaluation methodology demonstrates several key characteristics:

- Scalability: Decision-based reassessment reduces unnecessary computations.
- Granularity: Batch-level evaluation captures variations in real-world production conditions.
- Explainability: AI-assisted sustainability indicators provide interpretable insights.
- Integrability: The methodology integrates seamlessly with traceability, verification, and transparency modules within the EcoTrace framework.

VI. PROTOTYPE IMPLEMENTATION AND QUALITATIVE EVALUATION

To validate the feasibility of the proposed EcoTrace framework, a prototype system was developed that demonstrates the integration of traceability, sustainability evaluation, verification mechanisms, and consumer transparency within a unified architecture. The primary objective of the prototype implementation is to evaluate the practicality of the framework design and to demonstrate how the different modules interact in a real system environment.

The prototype system follows the modular structure described in the EcoTrace framework. It consists of a web-based frontend interface, backend service layer, and a database layer for data storage. The frontend provides interfaces for producers to register products and batches, while the backend manages data processing, sustainability evaluation, and transparency information retrieval. The system stores product and batch-level data within a structured database that supports traceability and sustainability record management.

The product definition and batch tracking modules were implemented to simulate real-world production scenarios. Producers can define products and create manufacturing batches, each containing attributes such as material composition, sourcing information, production details, and logistics parameters. These attributes are stored as structured records and serve as inputs to the sustainability evaluation module.

The sustainability evaluation module applies the decision-based evaluation methodology described in Section V. When a new batch is registered, the system compares its attributes with previously evaluated configurations. If significant variations are detected, sustainability evaluation is triggered; otherwise, previously generated indicators may be reused. This mechanism demonstrates the efficiency benefits of conditional reassessment in environments where production attributes remain consistent across multiple batches.

The prototype also integrates a QR-based transparency mechanism that links physical products to their digital sustainability records. For each product batch, the system generates a unique QR code associated with the batch identifier. When consumers scan the QR code using a mobile device, they are directed to a transparency interface that displays sustainability indicators, production information, and verification status for the specific batch. QR-based information access has been widely recognized as an effective mechanism for connecting physical products with digital information systems [7].

The prototype implementation focuses primarily on validating system feasibility and architectural coherence rather than optimizing performance for large-scale deployment. Therefore, the evaluation of the prototype is conducted qualitatively based on the following criteria:

• Modularity: Ability of the framework to separate system responsibilities into independent components.

• Transparency: Clarity and accessibility of sustainability information provided to consumers.

• Evaluation Efficiency: Effectiveness of the decision-based sustainability reassessment mechanism.

• Extensibility: Capability of the architecture to support future enhancements such as additional sustainability indicators or verification mechanisms.

The qualitative evaluation indicates that the EcoTrace framework successfully integrates traceability, sustainability evaluation, and consumer transparency into a coherent system architecture. The modular design allows each component of the system to operate independently while maintaining interoperability with other modules. Additionally, the QR-based transparency interface demonstrates how sustainability information can be delivered directly to consumers in an accessible and scalable manner.

Although the prototype demonstrates the feasibility of the proposed framework, large-scale empirical evaluation and real-world deployment remain important directions for future work. Further research may explore integration with real supply chain datasets, performance evaluation in large-scale environments, and user studies to assess consumer understanding of sustainability indicators.

VII. DISCUSSION

The qualitative evaluation of the EcoTrace prototype demonstrates the feasibility of integrating product traceability, sustainability evaluation, and consumer transparency within a unified framework. By organizing the system into modular components, EcoTrace provides a flexible architecture that can support the evolving requirements of sustainability monitoring and digital transparency systems.

One of the primary strengths of the EcoTrace framework is its modular design. Separating product definition, batch lifecycle tracking, sustainability evaluation, verification, and consumer transparency into independent modules allows the system to scale more easily and adapt to future technological developments. Modular architectures are widely recognized as effective for building scalable and maintainable digital systems, particularly in complex environments such as supply chain management [3], [4].

Another important contribution of the framework is the introduction of batch-level sustainability evaluation. Traditional sustainability labeling approaches often treat products as static entities, which may overlook variations in materials, sourcing, or production conditions across different manufacturing cycles. By evaluating sustainability attributes at the batch level, EcoTrace captures real-world variability more accurately and improves the contextual reliability of sustainability information.

The decision-based sustainability reassessment mechanism also contributes to system efficiency. Instead of performing sustainability analysis for every batch regardless of similarity, the framework evaluates whether reassessment is necessary based on detected attribute changes. This approach reduces redundant computations and improves scalability in production environments where many batches share similar configurations.

In addition, the framework emphasizes interpretability in AI-assisted sustainability evaluation. Explainable AI methods help ensure that automated assessments remain transparent and understandable to users, which is essential for building trust in AI-supported decision systems [5], [6]. By associating sustainability indicators with contributing factors, the system enables consumers to better understand how sustainability evaluations are derived.

The integration of QR-based transparency mechanisms further enhances accessibility of sustainability information. QR codes provide a simple and cost-effective method for linking physical products to digital records, allowing consumers to retrieve product information quickly using mobile devices. Previous research has shown that improved traceability and accessible product information systems can increase consumer trust and influence purchasing behavior [7].

Despite these strengths, the current study has several limitations. The prototype implementation focuses primarily on demonstrating architectural feasibility rather than evaluating system performance at large scale. Additionally, the sustainability evaluation model relies on structured attribute inputs, which may vary in availability or accuracy across different industries. Ensuring consistent and reliable sustainability data remains a significant challenge for transparency systems.

Future research should therefore focus on large-scale empirical evaluation, integration with real supply chain datasets, and user-centered studies to assess how consumers interpret and use sustainability indicators. Further investigation into standardized sustainability data schemas and improved AI models may also enhance the reliability and usability of sustainability transparency systems.

VIII. CONCLUSION AND FUTURE WORK

This paper presented EcoTrace, a modular framework designed to enhance product sustainability transparency through the integration of product traceability, AI-assisted sustainability evaluation, and QR-based consumer access mechanisms. The proposed framework addresses limitations in existing sustainability communication approaches by connecting product lifecycle tracking, structured evaluation methods, and consumer-facing transparency within a unified architecture.

Traditional sustainability labeling systems often provide static and limited information that is difficult for consumers to verify. In contrast, EcoTrace introduces batch-level traceability, enabling the system to capture variations in production attributes across manufacturing cycles. This approach improves the contextual accuracy of sustainability information and supports more reliable sustainability representation for individual product batches.

The framework also incorporates a decision-based sustainability reassessment mechanism, which improves efficiency by reducing redundant evaluations when production conditions remain unchanged. By combining this mechanism with AI-assisted analysis, the framework enables scalable sustainability evaluation while maintaining transparency through interpretable indicators. The integration of QR-based transparency mechanisms further allows consumers to access sustainability information directly through mobile devices, improving accessibility and supporting informed purchasing decisions.

A prototype implementation was developed to validate the architectural feasibility of the EcoTrace framework. The qualitative evaluation demonstrates that the proposed architecture successfully integrates traceability, sustainability assessment, verification mechanisms, and consumer transparency within a modular system structure. The results indicate that the framework provides a practical foundation for developing digital systems that promote sustainability transparency and responsible consumption.

Although the proposed framework demonstrates conceptual feasibility, several directions remain for future research. Future work may include large-scale empirical evaluation using real supply chain datasets, development of standardized sustainability data schemas, and exploration of advanced AI models for improved sustainability assessment. Additional research may also investigate integration with decentralized verification technologies and regulatory sustainability reporting frameworks.

In conclusion, EcoTrace provides a scalable and extensible framework for sustainability-focused digital transparency systems. By integrating traceability, evaluation, and consumer accessibility within a unified architecture, the framework contributes toward improving product transparency and supporting more sustainable consumption practices.

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