Simplified Produce Labeling: Enhancing AI-Readiness, Data Integrity, and Accessibility in the Bioeconomy

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Abstract: The rapid digitization of agriculture and food systems, central to the growing global bioeconomy, necessitates robust, transparent, and universally accessible data infrastructure. This paper addresses consumer confusion resulting from complex product labels or labels in other languages by proposing a Simplified Produce Labeling Scheme (SPLS) that leverages technological integration to enhance trust and accessibility. The system translates complex production methods (e.g., Organic, Hydroponic) into an intuitive framework using distinct and unified symbols, color-coding, and an accompanying Index of Terms. Critically, the design integrates multiple modalities to impart information and ensure robust accessibility for consumers of diverse abilities. This scheme represents a foundational data layer for building trustworthy Agricultural Technology (AgTech) systems. The definitive formatted data generated by the labeling system is essential for ethical AI applications, preventing malicious interference and corporate capture in the food supply chain. We explore the technical integration of this project for secure, transparent tracking from farm to consumer, which reinforces certifiable proof of label accuracy and compliance with ethical production standards. Furthermore, the incorporation of secure smartphone apps and augmented reality (AR) for real-time information access positions the system as a model for participatory and interpretability-by-right user experiences in AI-driven data governance. Ultimately, this work presents a framework for simplified and standardized labeling with an emphasis on accessibility, accountability, and security.

Keywords: Food labelling, Artificial intelligence (AI), QR codes, Agricultural technology, Nutrition information

1. Introduction

Despite the proliferation of food product information, consumers frequently struggle to interpret labeling systems that remain complex, inconsistent, and often ambiguous (Li et al., 2023; Li et al., 2025). Although agricultural technology offers new opportunities to enhance supply chain transparency, establishing a unified labeling framework that is simultaneously verifiable, scalable, and accessible remains a significant challenge. Critical production data, including environmental impacts, labor practices, and ethical sourcing, are often omitted from or poorly presented on conventional labels, complicating consumer verification (Tiboni-Oschilewski et al., 2024). Consequently, systemic barriers such as challenges in information verification, regulatory fragmentation, implementation costs, and consumer distrust of AI continue to hinder the effectiveness of existing labeling strategies. Despite increasing food packaging information, complex eco-labels and information overload can hinder consumer decision-making (Cook et al., 2023; Tiboni-Oschilewski et al., 2024). While AI-enabled, interactive tools could convert production-level data into accessible insights, widespread AI distrust may impede adoption (Afroogh et al., 2024).

To address these limitations, we propose an *Inclusive Produce Labeling Scheme (IPLS)*, which combines an accessibility-oriented physical label with a persistent digital information layer accessible via QR codes or NFC. Rather than functioning solely as a static visual identifier, the label serves as an interoperable information interface that presents ingredients, allergen information, production practices, sustainability metrics, certifications, and supporting documentation using structured, AI-ready semantic data. This architecture enables consumers, including those relying on assistive technologies, to independently retrieve, interpret, and verify product information while reducing the cognitive burden associated with conventional labeling systems. In doing so, IPLS seeks to provide freely accessible, verifiable, and broadly distributable information that better reflects the technological capabilities of modern agricultural systems.

Improving transparency is particularly important for sustainability and certification claims because consumers increasingly rely on credible information about environmental stewardship, ethical production practices, and animal welfare when evaluating food products, and trust in those claims depends heavily on transparent, verifiable labeling (Cook et al., 2023). However, consumers frequently encounter labels such as organic, free-

range, cage-free, and made with recycled materials without understanding their underlying legal definitions, certification criteria, or verification methodologies. As a result, broad marketing terminology often obscures rather than clarifies product provenance. To address this gap, IPLS supplements conventional product labels with standardized explanations of certification schemes, regulatory definitions, and the evidence supporting those claims, allowing consumers to understand not only what a certification signifies but also how compliance is established and verified (Gaskin, 2025; McLeod et al., 2023).

The need for such transparency extends beyond certification labels to broader sustainability communication. Studies demonstrate that consumers frequently struggle to interpret numerical carbon-footprint labels, may experience cognitive overload when presented with excessive information, and often confuse greenhouse-gas emission metrics with indicators of contamination or food safety (Cook et al., 2023). AI-enabled labeling systems that integrate QR-code technologies can address these limitations by providing personalized, context-sensitive explanations that improve comprehension while reducing cognitive burden (Cook et al., 2023). Rather than replacing traditional labeling, AI functions as an interpretive layer that adapts information to individual consumer needs while maintaining direct links to verifiable source material. By combining machine-readable semantic data, transparent certification records, and human-centered interface design, IPLS transforms conventional food labels into evidence-based decision-support tools that enable informed purchasing decisions while promoting equitable access to trustworthy food information (Mariappan et al., 2025).

2. Method and Considerations

Our prototype development synthesizes literature regarding the shortcomings of contemporary produce labeling: information overload, limited transparency, and persistent consumer distrust (Cook et al., 2023; Tiboni-Oschilewski et al., 2024). These findings informed a framework transforming static labels into interoperable, accessibility-centered information systems suitable for the AI-enabled bioeconomy. Central to this approach is "accessibility by design," redefining labels not merely as visual communication but as structured, machine-interpretable data accommodating diverse sensory and cognitive needs. We identified three key design requirements: (i) proximity-based digital interaction via NFC or QR, (ii) tactile physical affordances for non-visual interaction, and (iii) standardized semantic data structures enabling interoperability with assistive technologies and AI.

Our prototype integrates two complementary components: physical labels incorporating tactile features (e.g., embossed stickers) and a persistent digital interface accessible via NFC or QR scanning. This dual-layer architecture enables access to ethical production data, certifications, allergen information, and sustainability metrics in both human and machine-readable forms. By combining physical accessibility with interoperable semantic data, this scheme transforms conventional labels into inclusive interfaces, allowing consumers, regardless of sensory ability, to independently access and verify product provenance and ethical attributes. However, directly applying extensive tactile formatting (such as Braille) onto small individual items like garlic bulbs or key limes presents clear physical limitations. To address this, the framework accommodates flexible secondary placement strategies rather than forcing all data onto individual item surfaces. For small produce, essential tactile and digital markers can be located on outer packaging, storage containers, or dedicated shelf bins. Alternatively, dynamic smart signage positioned within the retail environment can broadcast identical semantic data directly to assistive mobile devices, ensuring full accessibility without overloading individual product items.

3. Provisional Prototype and Considerations Toward Operationalizing

To operationalize our framework, the Transparency Facts prototype (Figure 1) translates complex sustainability, ethical, and safety information into a unified interface. The design leverages high-contrast typography, standardized iconography, and semantic architecture to minimize cognitive burden while improving usability for diverse consumer populations. Accessibility is further enhanced through tactile physical affordances, NFC-enabled tags, and assistive technology support, enabling users with varying sensory and cognitive needs to access information without reliance on printed text.

Digital integration extends the label beyond the physical surface. QR codes and data-matrix identifiers connect products to interoperable, machine-readable data, including production audits, allergen profiles, sustainability metrics, and certification records, via consistent semantic formats. These digital portals provide access to peer-reviewed evidence, regulatory documentation, and AI-based conversational agents that answer consumer inquiries using authenticated source material. Figure 1A illustrates a compact implementation for individual items, while Figure 1B presents a denser layout appropriate for larger packaging. Collectively, the prototype

demonstrates how intentional interface design, coupled with interoperable data governance, transforms conventional product labels into inclusive and extensible information systems that foster informed decision-making.



1A: Tactile Stickers and E-Scanner Friendly Engravings/ Sprayings containing most immediate information, plus a QR code or dot-matrix leading to information-dense portal. These are meant for single produce labeling.
1B: Information-dense pages that can lead to even further information dense pages, for those who either need further specificity for their nutritional needs, work in the agri-data professions, work in regulation, and or otherwise need further underlying data. This page is meant to serve lay audiences while further portals serve deeper. This can also be applied to produce packages.

Figure 1: The "Transparency Facts" Multi-modal Labeling Prototype. (1A) Shows stickers with quick-reference icons for immediate audience identification. (B) The corresponding "Transparency Facts" digital interface presents standardized, AI-ready data on sustainability, animal welfare, and production integrity. This system transforms static packaging into a dynamic, interoperable data node, enhancing consumer comprehension and agency through verified, machine-readable information, with multilingual support

4. Discussion

As AI integrates into the bioeconomy, product labels may evolve from static displays into dynamic, interoperable interfaces. Ensuring an equitable transformation requires labeling systems to adopt AI-ready, accessibility-first standards. Crucially, establishing a standardized, machine-readable semantic data layer supported by immutable and verifiable source records must precede any AI integration, which prevents corporate capture and malicious interference in the food supply chain by anchoring automated summaries in auditable truth. Accordingly, our Inclusive Produce Labeling Scheme (IPLS) may encode data as structured, semantic information simultaneously human-readable and machine-interpretable, enabling assistive technologies to convey production practices, environmental impacts, allergens, and certifications without visual or proprietary limitations. This shifts labeling from passive disclosure toward participatory agency, empowering individuals, including those with visual impairments, to engage autonomously with the food system. Policy must prioritize universal, open, machine-readable data standards as foundational requirements for AI-enabled information systems.

Accessible infrastructure is also vital for sustainability labeling. While consumers often pay premiums for sustainable products, label effectiveness relies on clear, credible communication (Cook et al., 2023). Consumers frequently struggle with complex numerical carbon-footprint metrics, experiencing cognitive overload or misinterpreting greenhouse-gas indicators as safety metrics rather than environmental impacts (Cook et al., 2023). AI-assisted, QR-enabled systems offer solutions by delivering personalized, context-sensitive explanations that improve comprehension and reduce cognitive burden (Mariappan et al., 2025). This framework also applies to over-the-counter (OTC) medications and pharmaceuticals, where the absence of standardized, accessible data creates critical informational gaps. Implementing universal, AI-ready designs can synthesize fragmented data into actionable health insights, standardizing information delivery and enhancing patient safety.

5. Operational Challenges and Governance Considerations

Operationalizing IPLS requires more than developing a consumer-facing labeling mechanism. Its effectiveness depends on the political, institutional, and technical arrangements through which participating countries adopt common standards, store and exchange data, verify information, and correct disputed claims. As a work in progress, IPLS is therefore best understood as establishing a set of governance requirements that future implementations would need to satisfy to achieve interoperability, trust, transparency, and equitable participation.

5.1 International Governance and Adoption

Given the transnational nature of food supply chains, widespread implementation of IPLS requires coordinated international governance. Since no single existing organization oversees the full spectrum of agriculture, food safety, trade, and digital standards, we propose a multi-stakeholder framework. This model would establish core, interoperable data requirements while allowing national governments to maintain regulatory authority over jurisdiction-specific policies.

Implementation must navigate complex political and technical challenges, including varying definitions of sustainability and animal welfare, as well as concerns regarding compliance costs and trade barriers. To mitigate these, IPLS distinguishes between essential, globally interoperable core requirements and supplementary, region-specific information. Consequently, a phased adoption strategy, leveraging voluntary standards, pilot programs, and industry-led initiatives rather than immediate, top-down universal regulation, provides the most viable path toward broad governmental adoption and long-term standardization.

5.2 Data Infrastructure, Storage, and Integrity

IPLS efficacy hinges on data reliability, but does not necessitate a centralized global database. Instead, it utilizes a federated architecture where records remain within existing public regulatory databases, accredited certification systems, and verified private repositories. This allows data custodians-regulators, producers, and certifiers to maintain control while adhering to shared standards for security, interoperability, and provenance.

To ensure integrity, IPLS prioritizes authenticated source records over unrestricted web scraping. Technical safeguards such as digital signatures, tamper-evident logs, and cryptographic verification can confirm provenance, though they do not guarantee factual accuracy; institutional verification remains essential. Finally, this architecture adheres to data minimization principles, ensuring transparency without compromising commercially sensitive information or personal data.

5.3 Data Sources, Trust, and AI Interpretation

IPLS clearly distinguishes evidence from interpretation. Authoritative regulatory, certification, and producer records form the primary verification layer, with all sustainability and ethical claims linking directly to identifiable sources, standards, and verification dates. AI systems serve strictly as interpretive interfaces that summarize verified data rather than autonomous arbiters of truth. Earlier studies demonstrate AI-mediated analysis of consumer content, such as extracting product attributes (Hu and Liu, 2004), predicting ratings from text (McAuley and Leskovec, 2013), and classifying deceptive reviews (Ott et al., 2011), yet these methods do not establish AI outputs as independent evidence or arbiters of truth. Where source data is incomplete or contested, IPLS must explicitly report that limitation instead of generating unsupported conclusions.

5.4 Oversight and Supply-Chain Monitoring

Continuous manual review of complex global food supply chains is impractical, making automated oversight necessary to monitor structured data for discrepancies such as expired certifications, conflicting origin data, or unauthenticated claims. However, automated anomaly detection flags potential issues rather than proving misconduct. The resulting model is hybrid: automated systems provide scalable screening across large datasets, while accountable human auditors and regulatory authorities handle contextual and ethical evaluations. This design ensures scalable oversight without relying on autonomous AI to independently validate global supply chains.

5.5 Dispute Resolution, Correction, and Auditability

IPLS must include a transparent dispute resolution mechanism, allowing stakeholders such as consumers, producers, and regulators to flag inaccurate, outdated, or misleading information. Reported discrepancies trigger a formal verification process. During investigation, contested claims should be marked as "under review"

rather than presented as verified fact, ensuring transparency. Once resolved, corrections update the digital label while maintaining a versioned audit trail. This history, documenting the nature of the change and the responsible authority, ensures accountability and allows the system to evolve while maintaining a permanent record of evidentiary changes.

5.6 Equity and Implementation Capacity

IPLS inclusivity requires addressing technological, financial, and institutional disparities across agricultural systems. Criticism of costly soil testing highlights the need to consider the expense and local applicability of verification requirements (Only Organic, 2024). Thus, IPLS should provide flexible pathways to meet uniform evidence standards without overburdening smallholders. While well-resourced operations can adopt automated or cryptographic verification, smaller entities could verify claims through cooperatives, public authorities, or accredited intermediaries. These adaptable pathways maintain evidentiary quality while respecting local capacities, fostering global interoperability, and reducing barriers to entry.

6. Limitations

There are obviously limitations to the operationalization of the concepts presented. The largest is the lack of a coherent, overarching international framework that consolidates food safety standards and data into a single repository. Food standards vary widely across countries and should be standardized for international shipping. Labeling, which could be understood across countries, would be difficult enough for laypeople to grasp. This, of course, does not address the intentional obfuscation of labor practices surrounding the production of certain foodstuffs. To keep international standards high and to verify them would require a corps of inspectors. This could be an opportunity to have a globally aware corps of agronomists during a time of monumental climate change. This corps could find better ways to grow food around the world and bring those concepts back to their home country.

7. Conclusion

With the integration of AI-enabled labeling, consumers can be further empowered to navigate the complex, fragmented information ecosystem of modern food production with additional clarity. By synthesizing disparate production data into an interoperable, AI-ready architecture, this scheme allows dynamic access to critical product knowledge while dismantling informational barriers. Crucially, this inclusive design ensures that both disabled and non-disabled users can interact with the supply chain autonomously and equitably. As we look toward the future of AgTech, policy initiatives must prioritize such universal, semantic data standards to safeguard consumer rights and foster a resilient, transparent bioeconomy. Ultimately, this framework offers a scalable blueprint for leveraging AI not merely as a technical instrument, but as a foundational pillar for a more informed, just, and accessible global food marketplace.

AI Tool Declaration: Gemini and ChatGPT were used to assist with image assistance, organizing, and refining this paper's content, grammar, and structure.

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