Review Article

Building Trustworthy Traceability Systems in Sustainable Used Cooking Oil Supply

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Abstract

The growing global emphasis on sustainability and renewable energy has underscored the importance of establishing credible traceability systems in used cooking oil (UCO) supply chains to ensure environmental protection and regulatory compliance. This study aims to develop a comprehensive framework for a reliable traceability system that supports sustainable UCO supply. Using a qualitative literature review approach, the research systematically synthesises findings from over eighty relevant academic articles and reports, managed via Mendeley Desktop. Data collection involved an extensive review of peer-reviewed journals, policy papers, and industry publications focused on UCO traceability, supply chain management, and technological innovations. The data were analysed through thematic content analysis to identify critical challenges, technological advancements, regulatory environments, and best practices. Results indicate significant obstacles such as supply chain fragmentation, inconsistent regulations, low adoption of digital tools, and the dominance of informal collection networks. Promising approaches include blockchain-based systems for tamper-proof tracking, QR code technologies for transparency, multi-stakeholder collaborations, and improved policy enforcement mechanisms. The study finds that integrating technological solutions with robust institutional frameworks is essential to enhance transparency, data integrity, and scalability in traceability systems. In conclusion, the development of credible traceability mechanisms can contribute significantly to sustainable biodiesel production from UCO by ensuring compliance and reducing environmental risks. Future research is encouraged to empirically validate proposed frameworks and examine behavioural factors affecting stakeholder participation across various regions to improve system adoption and effectiveness.

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Introduction

In recent decades, the global push for sustainable development has amplified the demand for circular economy practices that emphasize waste valorization and resource optimization [1]. Among various waste streams, used cooking oil (UCO) has garnered significant attention due to its potential as a renewable feedstock for biodiesel production, bio-lubricants, and other biobased materials [2]. The transformation of UCO into valuable products contributes not only to energy security but also to the mitigation of environmental risks associated with improper oil disposal [3]. However, despite its promise, the management of UCO remains largely fragmented, informal, and unregulated in many regions, posing significant risks to both environmental sustainability and public health [4].

One of the most pressing issues in the current UCO supply chain is the lack of traceability and accountability mechanisms. In the absence of a credible traceability system, UCO often re-enters the food supply chain illegally, a phenomenon reported in both developed and developing economies [5]. This illicit practice not only jeopardizes food safety but also undermines public trust in food regulatory systems [6]. Moreover, the inability to verify

the origin, handling, and processing of UCO hinders the effective enforcement of environmental and quality standards [7].

The concept of traceability, defined as the ability to track the history, application, or location of an entity through recorded identification data, is a cornerstone in the governance of complex supply chains [8]. In the agri-food and biofuel sectors, traceability ensures that products comply with sustainability certifications, legal regulations, and ethical sourcing standards [9]. A robust traceability framework is especially vital for UCO, whose collection networks often involve multiple stakeholders—from households and restaurants to collectors, aggregators, and processors - each with varying degrees of regulatory oversight [10].

Developing a credible traceability system for UCO requires addressing multidimensional challenges, including technological capability, data standardization, stakeholder alignment, regulatory compliance, and consumer awareness [11]. Emerging digital technologies such as blockchain, IoT, and QR coding have demonstrated potential to improve traceability across diverse supply chains, yet their adoption in UCO systems remains limited and fragmented [12]. This gap is further exacerbated by inconsistent data management practices, lack of interoperability between platforms, and high implementation costs for small-scale actors [13].

Literature on traceability in supply chains suggests that credibility is contingent upon four key attributes: transparency, verifiability, interoperability, and real-time accessibility [14]. In the case of UCO, these attributes are particularly critical due to the risk of contamination, illegal resale, and regulatory evasion [15]. A traceability system that fails to address these factors may result in "traceability in name only," where data exists but cannot be meaningfully verified or acted upon [16]. Therefore, the emphasis must shift from mere trace recording to ensuring systemic credibility and trustworthiness.

Several countries have initiated national frameworks to regulate UCO collection and conversion, often integrating traceability as part of biodiesel certification processes [17]. However, many of these frameworks suffer from limited scalability, low stakeholder participation, and inadequate enforcement mechanisms [18]. Without credible systems in place, the sustainability claims of biofuel production from UCO become difficult to validate, thus undermining efforts to achieve broader environmental targets such as those outlined in the Paris Agreement and the UN Sustainable Development Goals (SDGs) [19].

In addition to environmental imperatives, there are strong economic incentives to formalise the UCO supply chain. Traceability systems enable producers to access premium markets, secure certifications, and ensure compliance with international trade regulations, particularly in the European Union and North America [20]. Nonetheless, the absence of standardised approaches and interoperable platforms across borders limits the global potential of sustainable UCO trade. As such, a literature-based synthesis is necessary to identify foundational principles, structural components, and implementation strategies that can guide the development of a credible, scalable, and sustainable traceability system for UCO.

Given these complexities, the current study adopts a Qualitative Literature Review (QLR) approach to explore how traceability systems in UCO supply chains have been conceptualised, implemented, and evaluated in previous academic and policy literature. Unlike field-based research such as focus group discussions or observational case studies, QLR allows for an in-depth theoretical and empirical synthesis across a broad range of contexts and perspectives without relying on primary data collection. This method is particularly relevant given the interdisciplinary nature of the subject, which intersects environmental science, supply chain management, digital governance, and public policy.

The objective of this study is to develop a conceptual framework for a credible traceability system tailored to the unique challenges of the UCO supply chain. Specifically, the review seeks to

a) identify the key components and characteristics of existing traceability models

b) examine the enabling and inhibiting factors for system credibility

c) propose a strategic pathway for the design and adoption of an integrated traceability solution that supports both sustainability and regulatory compliance.

By synthesizing over 80 peer-reviewed sources across multiple disciplines, this article aims to contribute actionable insights for researchers, policymakers, and industry stakeholders committed to advancing circular economy practices through traceable and sustainable UCO systems.

Literature Review

The concept of traceability in supply chain systems has evolved from a compliance-oriented tool to a strategic enabler of transparency, accountability, and sustainability. In the context of waste-to-resource value chains, traceability plays a central role in ensuring product integrity, especially in sectors where raw materials are derived from informal or decentralized sources such as used cooking oil (UCO) [21]. UCO, while recognized as a valuable renewable input for biodiesel and other bio-based industries, presents inherent challenges in traceability due to its dispersed generation points, inconsistent collection methods, and limited regulatory enforcement [22].

Early literature on food and feed supply chains introduced the idea of traceability mainly as a risk management instrument, focusing on recalls and food safety interventions [23]. Over time, the scope broadened to encompass environmental and ethical dimensions, especially in global value chains where visibility across actors and borders became increasingly critical [24]. For UCO supply chains, where risks include contamination, illegal reuse in food, and fraudulent mislabeling, credible traceability is not merely a regulatory requirement but a sustainability imperative [25].

Credibility in traceability systems depends not only on data capture but also on data integrity, verification mechanisms, and stakeholder trust. Various studies emphasize that traceability without verifiability leads to a superficial compliance layer that obscures rather than reveals supply chain realities [26]. For example, platforms that rely solely on self-declaration or fragmented documentation often fall short of providing actionable insight or deterrence against malpractice [27]. In UCO systems, which often involve small-scale and informal collectors, the lack of standardized reporting formats and authentication tools severely hampers credibility [28].

Technological innovation has provided promising pathways to enhance traceability. Blockchain, with its immutable ledger and decentralized validation, is frequently cited as a transformative tool for traceability in agri-food and energy sectors [29]. However, its successful application in UCO supply chains remains limited, primarily due to the complexity of onboarding low-tech stakeholders and the high cost of implementation [30]. Other technologies such as QR coding, GPS tracking, and IoT sensors offer more accessible alternatives but may still face adoption barriers where infrastructure and digital literacy are lacking [31].

Institutional frameworks also play a crucial role in shaping the credibility of traceability systems. Regulatory mandates, public–private partnerships, and third-party certifications can reinforce traceability goals by creating legal and reputational incentives [32]. Yet, literature shows that fragmented governance across jurisdictions can hinder interoperability and reduce system effectiveness [33]. In regions with minimal oversight, voluntary schemes or industry-led initiatives often emerge as substitutes, but their credibility depends on external auditability and stakeholder inclusiveness [34].

Another dimension frequently discussed is data governance. Traceability systems that prioritize transparency must simultaneously address concerns around data privacy, security, and ownership [35]. In the UCO context, where actors may be reluctant to share operational data due to fears of regulation or competition, designing secure yet open data environments is essential [36]. Studies suggest that participatory design involving all tiers of the supply chain can increase system buy-in and reduce data manipulation [37].

From an operational standpoint, the success of traceability systems is closely tied to supply chain structure and coordination mechanisms. Centralized models, often seen in corporate supply chains, offer control but may limit scalability in decentralized UCO networks. In contrast, federated or distributed models provide flexibility but demand higher levels of coordination and mutual trust [38]. Literature points to the importance of hybrid governance, combining formal regulation with informal norms, especially in emerging economies [39].

There is also growing recognition of the role of consumer pressure and market access in motivating firms to adopt traceability practices. In global biodiesel markets, sustainability certifications increasingly require evidence of traceable feedstocks, prompting exporters to upgrade traceability infrastructure [40]. However, unless credibility is built into the system design through third-party verification, open data policies, and stakeholder engagement, traceability risks becoming a performative rather than substantive tool.

Despite the diversity of contexts, existing studies converge on the notion that credible traceability for UCO must be designed with a systems perspective, considering not just the technological tools but also institutional incentives, stakeholder capabilities, and socio-economic realities. This literature review highlights a clear gap in the integration of these dimensions into a unified framework tailored to UCO, especially in supply chains characterized by informality, regulatory ambiguity, and cross-sectoral complexity. Building on these insights, this article seeks to develop a conceptual model for credible UCO traceability grounded in interdisciplinary literature and aligned with sustainability transitions.

Methodology

This study adopts a qualitative research design employing the qualitative literature review (QLR) approach to explore and conceptualize a credible traceability system for sustainable used cooking oil (UCO) supply chains. QLR is selected due to its strength in synthesizing diverse perspectives and theoretical constructs from existing scholarly works, enabling a deep, contextual understanding of complex, multidisciplinary phenomena without the need for primary data collection. Unlike systematic literature reviews (SLR), which emphasize replicability and exhaustive search protocols, QLR emphasizes interpretative depth and conceptual integration, making it especially suitable for theory-building within emerging and fragmented research areas.

The primary instrument in this study is the researcher as an analytical agent, who critically examines, selects, categorizes, and synthesizes knowledge from previous academic publications across relevant domains, including supply chain traceability, sustainability governance, digital systems, waste valorization, and renewable energy transitions. Data for this study were gathered through a structured search of academic databases such as Scopus, ScienceDirect, Wiley Online Library, and SpringerLink, focusing on peer-reviewed journal articles published predominantly within the last ten years. The inclusion criteria emphasized conceptual relevance, methodological rigor, and empirical richness, while exclusion criteria involved redundancy, limited scope, and unverifiable sources. Mendeley Desktop was utilized as the reference management tool to ensure accurate citation, traceability of sources, and seamless integration into the manuscript. The analytical process involved thematic coding, conceptual mapping, and constant comparison to identify patterns, theoretical gaps, and emergent constructs related to traceability credibility in UCO supply systems. This was done through multiple rounds of reading and abstraction, guided by a reflexive and iterative logic, to develop a conceptual model grounded in literature rather than empirical observation. The validity of the review was reinforced by triangulating findings across disciplines and critically contrasting dominant and alternative theoretical standpoints. Through this qualitative literature review, the study aims not to quantify relationships but to construct a comprehensive, theory-informed framework that can serve as a foundation for future empirical validation and policy design regarding credible traceability in sustainable UCO supply chains.

Results

This section presents the findings derived from a comprehensive qualitative literature review of existing research on traceability systems within used cooking oil (UCO) supply chains. The results are structured thematically to highlight the scope, challenges, technological innovations, regulatory frameworks, and emerging best practices across various geographical and industrial contexts. Rather than reporting empirical field data, the findings synthesize conceptual, policy-based, and empirical insights from prior studies to establish the foundational elements of a credible traceability system for sustainable UCO supply.

Sources and Nature of Used Cooking Oil (UCO) Supply Chains

Literature reveals that the global production of used cooking oil has reached approximately 29 million metric tons annually, with China, the United States, and the European Union accounting for over 60% of this total output [41]. However, only an estimated 20–25% of this volume is collected and repurposed sustainably,

Traceability Gaps and Supply Chain Vulnerabilities

The review identifies several traceability failures stemming from structural fragmentation. For instance, a study in Southeast Asia found that over 40% of UCO transactions were undocumented or cash-based, making them invisible to formal monitoring systems [45]. In Europe, despite the existence of stringent sustainability criteria under the Renewable Energy Directive II (RED II), audits uncovered that up to 12% of UCO used in biofuel production originated from unverifiable sources, undermining certification credibility [46]. This situation is exacerbated in regions lacking harmonised regulations, where traceability lapses are often exploited for fraudulent blending, including the reuse of UCO in food applications—a public health threat with severe ethical implications [47].

Existing Digital Traceability Technologies

Several digital technologies have been introduced in the literature to address traceability challenges. Blockchain platforms, for example, have demonstrated effectiveness in creating tamper-proof chains of custody, but adoption remains limited. A pilot in the Netherlands showed that blockchain could reduce data discrepancies by up to 95% across UCO value chains [48], but operational costs and onboarding complexity remain high, particularly for smallholders [49]. QR code-based systems have been more widely adopted in Asia, where one program in Malaysia improved traceable UCO collection volumes by 38% within a 12-month trial period [50]. However, technological solutions alone have proven insufficient when not supported by institutional and behavioral alignment among actors [51].

Institutional and Policy Frameworks for UCO Traceability

The regulatory landscape for UCO traceability is inconsistent globally. In the EU, RED II mandates sustainability certification for biofuels, including documentation of feedstock origin, but enforcement varies by member state [52]. In contrast, countries like India and Indonesia lack binding traceability protocols for UCO, resulting in regulatory blind spots that facilitate illegal reuse or improper disposal [53]. Public-private partnerships have emerged as critical enablers of traceability. In Germany, a consortium-led model involving municipalities and private collectors led to a 46% increase in traceable UCO over three years [54]. This indicates that multi-stakeholder collaboration, supported by clear regulatory mandates, plays a significant role in enhancing data reliability and system transparency [55].

Economic and Environmental Drivers

The demand for traceable UCO is being driven by the rapid expansion of the global biodiesel market, which was valued at USD 41.2 billion in 2022 and is expected to reach USD 64.5 billion by 2027 [56].

UCO-derived biodiesel offers lifecycle greenhouse gas (GHG) savings of up to 88% compared to fossil diesel [57]. However, such benefits can only be claimed under certification schemes that require verifiable traceability. Data indicate that traceable UCO fetches 15–30% higher prices in international markets than non-traceable counterparts, creating a strong economic incentive for traceability compliance [58]. Despite this, informal collectors and aggregators—who account for up to 70% of UCO flow in developing regions—often lack access to traceability-enabling infrastructure [59].

Analytical Themes: Credibility Enablers and Constraints

From the synthesis of literature, four key themes emerge as critical to traceability credibility: data integrity, interoperability, actor participation, and external verification. Studies emphasise that without real-time, verifiable data, traceability claims are susceptible to greenwashing or manipulation [60]. Interoperability between systems remains a barrier, particularly where government databases, private registries, and certification bodies operate in silos. Moreover, literature shows that participation and trust among supply chain actors are prerequisites to sustainable traceability adoption. When traceability systems are co-developed with stakeholders and aligned with local practices, adoption rates increase substantially, by over 50% in some pilot projects.

Overall, the literature reviewed indicates that while the technological means to ensure credible traceability for UCO already exist, their effectiveness is constrained by sociopolitical, economic, and institutional barriers. The most promising systems are those that integrate low-cost digital tools with regulatory oversight and stakeholder inclusion. There is a growing consensus across disciplines that credible traceability must move beyond linear documentation and instead embrace dynamic, adaptive frameworks capable of responding to changing supply chain realities. Despite advances, a unified, scalable model that balances credibility, affordability, and inclusivity across the UCO sector remains elusive.

These synthesized findings form the basis for a broader discussion on implementation strategies, scalability, and the interplay between digital innovation and institutional frameworks in enabling credible traceability systems, which are elaborated in the following section.

Discussion

The objective of this study was to develop a credible traceability system for sustainable used cooking oil (UCO) supply by synthesizing existing knowledge from the literature. The findings reveal several critical insights into the complex dynamics influencing UCO traceability, highlighting both opportunities and barriers.

Firstly, the extensive global production of UCO, estimated at around 29 million metric tons annually, underscores the urgent need for robust traceability frameworks to ensure environmental and economic sustainability [61]. Despite this volume, only a fraction—approximately 20 to 25%—is effectively recovered and reused, a gap primarily attributed to informal supply chains and weak regulatory oversight [62,63]. This disconnect points to the necessity for traceability systems that can integrate fragmented actors, particularly in regions where informal vendors and household sources dominate supply streams [64]. The Indonesian context exemplifies these challenges, with less than 30% of generated UCO entering official recovery channels [65].

Secondly, the literature highlights systemic vulnerabilities caused by structural fragmentation and insufficient documentation within UCO supply chains [66]. These vulnerabilities compromise the credibility of sustainability claims and open avenues for fraudulent activities such as illicit reuse of UCO in food applications [67]. The exposure of unverifiable UCO sources in European biofuel production illustrates the global prevalence of traceability gaps despite stringent policies like RED II [68]. Therefore, bridging these gaps demands not only technological innovation but also institutional reforms to harmonise regulations and enforce compliance uniformly [69].

Technological advancements represent a promising solution but face adoption hurdles. Blockchain and QR code technologies have demonstrated significant improvements in data integrity and collection efficiency [70,71]. However, cost, complexity, and limited accessibility for smallholders constrain widespread implementation [72]. This underscores the importance of designing scalable, user-friendly digital tools that accommodate the diverse capabilities of supply chain participants. Moreover, technology alone is insufficient without parallel efforts to align institutional incentives and promote behavioural change among stakeholders [73].

Institutional and policy frameworks vary markedly across regions, affecting traceability outcomes. While the European Union enforces mandatory sustainability certifications under RED II, countries such as India and Indonesia exhibit regulatory voids that impede traceability enforcement [74]. Public-private partnerships emerge as vital mechanisms to enhance transparency and foster collaboration, as demonstrated by the 46% increase in traceable UCO in Germany's consortium-led initiatives [75]. This exemplifies how multi-stakeholder governance can leverage complementary strengths, combining regulatory mandates with localized operational expertise [76].

Economic and environmental drivers further motivate traceability adoption. The burgeoning global biodiesel market, valued at over

USD 41 billion and expected to reach USD 64 billion by 2027, incentivizes traceable UCO through premium pricing and certification-linked lifecycle greenhouse gas (GHG) reductions of up to 88% [77,78].

Despite these drivers, a significant portion of UCO - particularly in developing regions - remains outside formal traceability infrastructures, limiting economic benefits for informal collectors and posing sustainability risks [79]. Addressing this gap requires policies that enhance access to traceability technologies and integrate informal actors into formal value chains.

Four critical themes underpin traceability credibility: data integrity, interoperability, actor participation, and external verification [80]. Data integrity safeguards against manipulation and greenwashing, while interoperability challenges persist due to siloed systems among governments, private entities, and certification bodies. Engaging supply chain actors through trust-building and participatory design emerges as a cornerstone for sustainable adoption, with pilot projects reporting adoption increases exceeding 50% when stakeholders co-develop systems [81]. External verification mechanisms provide essential oversight, reinforcing accountability and confidence in traceability claims.

Collectively, the literature indicates that an effective traceability system must transcend linear documentation to embrace dynamic, adaptive frameworks. Integrating low-cost digital tools with robust institutional oversight and inclusive governance can enhance scalability and sustainability. However, no unified model currently addresses the competing demands of credibility, affordability, and inclusivity comprehensively. This gap highlights an urgent research and policy agenda focused on designing holistic systems that respond flexibly to evolving supply chain contexts.

This study's findings have several implications for policymakers, industry stakeholders, and researchers. Policymakers should prioritize harmonizing traceability regulations and incentivizing technology adoption, especially among informal actors, to foster a more inclusive UCO supply chain. Industry players need to engage in collaborative governance models that promote transparency and share responsibility for sustainability outcomes. Researchers are encouraged to develop and empirically test integrated traceability frameworks that balance technological innovation with social and institutional realities.

Future research should explore longitudinal case studies to assess the real-world performance of traceability systems across diverse contexts. Investigations into cost-effective, user-centered digital solutions tailored for informal sectors can address existing barriers. Additionally, examining the socio-cultural factors influencing stakeholder participation will provide deeper insights into designing trust-based traceability systems.

By advancing a credible, scalable traceability system, this research contributes to enhancing the sustainability of UCO supply, ultimately supporting environmental goals, economic development, and public health.

Conclusion

The development of a credible traceability system for sustainable used cooking oil (UCO) supply chains necessitates a multifaceted approach that addresses the complex interactions among technological, institutional, economic, and social factors. The review highlights that global UCO production is substantial but largely informal, causing significant challenges in traceability due to fragmented supply chains and unregulated actors. These challenges are further compounded by inconsistent regulatory frameworks and limited enforcement, which create vulnerabilities for fraud and unsustainable practices.

Digital innovations, including blockchain and QR code-based systems, offer promising tools to enhance traceability by improving data integrity and transparency. However, the successful implementation of such technologies depends on their accessibility, affordability, and acceptance among diverse stakeholders, especially small-scale collectors and suppliers. The integration of these technological solutions with supportive institutional policies, public-private partnerships, and capacity-building initiatives is critical to ensure system reliability and stakeholder participation.

Economic incentives driven by the expanding biodiesel market and environmental benefits reinforce the importance of verified traceability, as traceable UCO commands premium prices and contributes significantly to greenhouse gas emission reductions. Nonetheless, bridging the gap between informal supply chains and formal traceability infrastructures remains a key barrier to widespread adoption.

Credibility in traceability is underpinned by real-time data verification, interoperability of systems, stakeholder trust, and independent external audits. Co-designed and contextually adapted frameworks demonstrate higher adoption rates and sustainability potential. Despite notable progress in technological and policy domains, a comprehensive, scalable, and inclusive traceability model that effectively balances cost, credibility, and participation has yet to be fully realized.

This synthesis underscores the imperative for coordinated efforts that combine technological innovation, regulatory harmonization, and stakeholder engagement to build resilient and sustainable UCO traceability systems. Future endeavors should prioritize inclusive system design and longitudinal evaluation to refine models and maximize both environmental and economic outcomes.

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