Smart sustainable solutions for improving coffee supply chain waste efficiency, traceability and introduction of key indicators for sustainability assessment

Nader Amir Fares*, Valentina Taverna*, Mizna Rehman, Ilaria Baffo*, Antonella Petrillo**, Fabio De Felice****

** Department of Economics Engineering Society and Business Organization (DEIM), University of Tuscia, Largo Dell'Universita s.n.c., Viterbo, Loc. Riello, 01100, (naderamir.fares@unitus.it, ilaria.baffo@unitus.it)*

*** Department of Engineering, University of Naples "Parthenope", Italy (mizna.rehman001@studenti.uniparthenope.it, antonella.petrillo@uniparthenope.it)*

Abstract: With millions of tons of coffee husks and due to inadequate supply chain procedures, spent coffee ground and damaged beans thrown away each year. While obstructing possible economic prospects, inadequate waste traceability, uneven regulatory enforcement, and limited valorization attempts further worsen environmental concerns. This paper examines the urgent need to improve the effectiveness and transparency of waste management, showing how supply chain processes can be improved to drastically cut waste and support sustainability goals. This study finds significant flaws in current supply chain governance and waste management strategies through a methodical analysis of policy reports, academic literature, and secondary data. The findings bring to light insufficient traceability mechanisms all along the chain, which can lead to struggles in resource recovery and difficulties in identifying where and why waste occurs. This issue may engender excessive losses at various stages and quality degradation. All these challenges can be mitigated through improved sustainable operational practices. The sustainability assessment of the coffee supply chain and its waste management remains a long, complex process. A major contribution of this study is the introduction of sustainability indicators, along with their variables and sub-variables, to systematically evaluate the environmental, economic, and social dimensions of coffee supply chain and its waste management. Results put forward a structured framework for evaluating sustainability and revealing critical intervention points for implementing digital traceability solutions, such as blockchain technologies and IoT-based monitoring systems. These technologies can significantly enhance waste tracking, optimize resource utilization, and reinforce compliance with national and international sustainability standards. By promoting a comprehensive approach that mixes policy reforms, innovative technologies, and upgraded stakeholder collaboration, this study suggests practical strategies for minimizing waste and optimizing the overall coffee supply chain efficiency. Strengthening traceability will be crucial in steering the coffee industry toward a more sustainable, resilient, and circular economic model.

Keywords**: Coffee waste, supply chain efficiency, traceability, sustainability assessment, blockchain, digital monitoring**

1. Introduction

Discussions of sustainability in the coffee supply chain have historically focused on upstream practices like organic or fair trade coffee. Correspondingly, downstream practices such as processing, distribution, consumption, and waste management have yet to receive as much academic and practitioner attention on the topic of sustainability (Bager et al., 2021). As commitment to sustainable production becomes more widespread globally, it is time to look to smarter, better metrics to improve efficiencies and increase resource recovery. In this case, technology like blockchain and internet of things (IoT) sensors offer the potential provide the necessary efficiencies in tracking waste in real time, increase transparency, and as an added benefit, increase compliance with local policies (Galvez et al., 2018; Lin et al., 2017). Yet, there is a lack of integrated frameworks that combine these innovations with clear sustainability assessment tools. This paper addresses that gap through a systematic understanding of the challenges of current waste management and traceability systems in the coffee supply chain. Drawing on literature reviews, policy documents, and secondary analysis, this study identified the fundamental challenges and identified how digital technologies, policy interventions, and stakeholder interactions could intersect together to enable a more circular economy. One of the primary contributions of this work is the development of a sustainability indicator set, which includes environmental, economic, and social criteria, that could support monitoring performance and be employed in some of the action planning. This paper is a critical examination of the challenges, but it also offers putative solutions to improve traceability, reduce waste, and promote the sustainable transformation of the coffee value chain.

2. Materials and methods

Using a qualitative, document-based research design, this research will examine smart and sustainable solutions for improving traceability and efficiency in the coffee supply

chain, and propose an integrated sustainability assessment indicator framework. The approach involves a purposive analysis of relevant secondary data sources (peer-reviewed academic literature, agency reports, policy papers, technical documents) relating to sustainability, waste management, and digital innovation in agri-food systems. The research considers documents published from 2010 to 2024, using documents obtained from search engines such as Scopus, Web of Science, and Google Scholar, and from agencies of record such as the International Coffee Organization (ICO), the Food and Agriculture Organization (FAO), and other agencies and institutions working in the general space of sustainability and development. he research considers documents published from 2010 to 2024, using documents obtained from search engines such as Scopus, Web of Science, and Google Scholar, and from agencies of record such as the International Coffee Organization (ICO), the Food and Agriculture Organization (FAO), and other agencies and institutions working in the general space of sustainability and development. The time frame starting from 2010 was chosen to reflect the period in which significant advancements in digital technologies—such as blockchain, IoT, and AI—began to be explored in agri-food systems. This also corresponds to the increasing institutional focus on sustainability and circular economy principles across international development agendas. The screening approach was based on a transparent selection process and followed systematic review procedures to identify and analyze materials in a dependable way. Inclusion criteria targeted documents that specifically addressed digital technologies such as blockchain, Internet of Things (IoT), radio-frequency identification (RFID), and sensor-based solutions in relation to supply chain traceability, as well as materials discussing waste valorization practices, circular economy approaches in the coffee sector, and sustainability assessment frameworks applicable to agri-food systems. Documents were excluded if they focused exclusively on unrelated agricultural products, lacked methodological transparency, or provided only general commentary without offering evidence-based insights or actionable frameworks. After screening, the selected documents were subjected to thematic analysis, where key patterns and recurring ideas were synthesized to reveal core challenges and opportunities within coffee supply chain governance and waste management. The analysis enabled the identification of promising innovations—such as blockchain-enabled certification systems and IoT-based monitoring networks—that can enhance supply chain visibility, support regulatory compliance, and promote a more circular economic model. Building upon these insights, the second part of the research involved developing a structured set of sustainability indicators designed to evaluate the environmental, economic, and social dimensions of the coffee supply chain. These indicators were derived from the reviewed literature and informed by established frameworks such as Life Cycle Sustainability Assessment (LCSA), the Global Reporting Initiative (GRI), and the Sustainability Assessment of Food and Agriculture Systems (SAFA). The indicators were articulated into a set of essential domains like reducing waste, managing resources efficiently, carbon footprint, equity in labor conditions, income distribution, and transparency; and were further developed into measurable variables and sub-variables that would be usable in various supply chain contexts. The two-part methodological approach of evidence synthesis and indicator development provides an overall framework to assess the sustainability performance of coffee supply chains while identifying leverage points to promote digital transformation and needed policy change (figure 1).

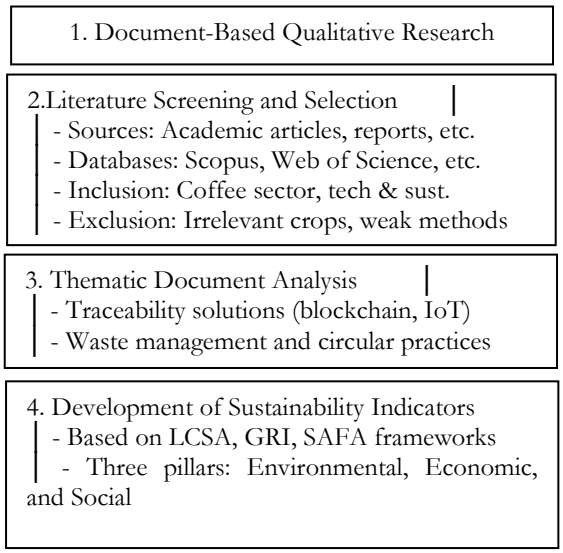

Figure 1. Methodology and important steps of the research

3. Main findings

The shift of the coffee supply chain toward a more sustainable and efficient system is reliant on the strategic implementation of digital technologies and new waste management procedures. The review of academic and institutional sources indicates a growing awareness of the need for integrated, smart solutions that use interoperability, rather than traditional linear supply chains (ICO, 2021; FAO, 2019). Practices within the current supply chain are hindered by uncoordinated data systems, inadequate traceability and processes that act reactively, rather than preventively (Samper & Quiñones-Ruiz, 2017). Emerging technologies like blockchain, IoT, AI, and mobile platforms have the potential to reshape the coffee value chain according to CO principles (Kamilaris et al., 2017; Galvez et al., 2018; Verdouw et al., 2016). Not only do these new technologies allow for real-time monitoring and transparency in each step of the chain, but they also support better decision making and accountability, from agricultural cultivation, processing and production to distribution and final consumption. Furthermore, the absence of a clear and standardized set of metrics to assess sustainability performance creates significant challenges when considering how to govern the coffee supply chain (UNEP, 2020; GRI, 2021). To address this, the study also proposes a set of structured indicators tailored to the environmental, economic, and social dimensions of the coffee supply chain. Together, these findings underscore the importance of technological innovation and robust assessment frameworks in

advancing a traceable, resilient, and low-waste coffee economy.

3.1. Blockchain for Transparent Traceability

Of the many nascent technologies that have the potential to impact sustainability in the coffee supply chain, blockchain is the most promising technology for improving data integrity, trust, and traceability. Blockchain is a distributed and decentralized digital ledger technology that stores transactions securely in immutable and time-stamped records without intermediaries and with the risk of manipulating data (Galvez et al., 2018). Blockchain may be applied to: record every moment in the life of a coffee bean, including planted, harvested, processed, transported along a chain of custody, to retail. Blockchain's potential is primarily the ability to store important information about the coffee's provenance (geographic location, farm practices), the conditions it was processed under (fermentation processes, drying standards), and any environmental and social certifications associated with it (Kamilaris et al., 2017). By providing access to real time data to each actor in the social supply chain - farmers, cooperatives, exporters, roasters, retailers, and eventually consumers - blockchain helps eliminate information asymmetry. It has the ability to verify claims related to organic production, fair trade compliance, and potentially even carbon footprint, thereby enabling companies to satisfy the growing consumer demand for ethical and sustainable products. A practical example would be to compare QR codes that link to blockchain systems to allow consumers to scan a package and see the entire history of their coffee - not only where it was grown but also how it was handled, how much waste was created in the processing, and if that company had met sustainability benchmarks. This level of detail builds brand trust while also allowing consumers to make assessments based on their values. In addition, blockchain systems can also be leveraged in connection with smart contracts, which are automatically executed contracts that are built into the blockchain that execute when certain, defined conditions are met (Tian, 2016). An example would be a contract that would only execute transferred payment to the producer when the traceability and environmental compliance information had been verified on the ledger. The verification would contribute to better practice, secure transactions and increase accountability. From a waste management perspective, blockchain can also track the quantities and types of waste generated at each stage of the supply chain, providing the basis for data-driven interventions. By pinpointing inefficiencies and losses, companies can optimize their operations, reduce overproduction, and enhance circularity strategies such as the valorization of spent coffee grounds and damaged beans. However, while the potential is vast, the integration of blockchain is not without its challenges. Effective implementation requires adequate digital infrastructure, especially in rural coffee-growing regions, as well as capacity building for smallholder farmers who may lack technical literacy. Moreover, interoperability between blockchain platforms, data standardization, and regulatory alignment remain unresolved issues that need coordinated attention from both the public and private sectors. Nonetheless, when deployed thoughtfully and inclusively, blockchain technology can serve as the digital backbone for a new model of governance in the coffee supply chain—one rooted in transparency, efficiency, and sustainability. By linking economic transactions with environmental and social performance, blockchain has the power to support systemic change and shift the industry closer to circular, low-waste production models.

3.2. IoT and Sensor-Based Monitoring for Real-Time Data and Resource Optimization

The Internet of Things (IoT), which allows real-time monitoring through networked devices and sensors, is another important technological pillar for enhancing sustainability and traceability in the coffee supply chain. From agricultural inputs and cultivation to processing, transportation, and retail, IoT systems are able to gather, send, and analyze data at almost every point of the coffee value chain (Verdouw et al., 2016). By maximizing water use, decreasing reliance on pesticides, and improving yield forecasting, soil moisture sensors, weather stations, and intelligent irrigation systems can help precision agriculture in agricultural settings. For climate-sensitive crops like coffee, where changes in temperature or rainfall can have a major impact on quality and productivity, these tools are especially helpful (Wolfert et al., 2017). Beyond the farm level, IoT-enabled gadgets like smart containers, GPS trackers, and RFID (Radio-Frequency Identification) tags provide better insight into how coffee beans are handled, stored, and moved during the post-harvest phases. For instance, spoilage risks can be identified by temperature and humidity sensors placed in warehouses or shipping containers, enabling actors to take action before deterioration takes place. This lessens waste and quality loss, two enduring issues in the coffee sector that are frequently hidden by conventional reporting systems. By enabling producers, traders, and buyers to confirm shipping schedules and keep an eye on delays that might compromise freshness and value, real-time logistics tracking also improves transparency. Additionally, IoT systems produce vast amounts of data that, when combined and examined, provide useful information for enhancing environmental performance and operational efficiency. Information gathered from processing facilities can be used to detect problems with roasting or drying equipment, identify excessive water use, and inform energy audits. Accordingly, IoT not only facilitates traceability but also acts as a basis for sustainability benchmarking and ongoing improvement throughout the supply chain (Brewster et al., 2017). Additionally, IoT has a lot of potential to help waste stream traceability. Businesses can determine where the majority of losses occur—during the harvesting, milling, packaging, or retail stages—and modify their resource recovery plans appropriately by tagging waste outputs and tracking their flow. Notwithstanding these benefits, there are a number of obstacles to IoT adoption in the coffee industry. These include the high upfront costs of software and hardware, the necessity of digital infrastructure and internet connectivity, especially in rural areas, and worries about

cybersecurity and data ownership. Furthermore, user training and organizational ability to analyze and act on the data gathered are critical to the long-term efficacy of IoT systems. However, IoT can be crucial to creating a coffee supply chain that is sustainable, low-waste, and digitally responsive when combined with complementary technologies like blockchain or AI-based analytics. It is one of the most adaptable tools in the industry's shift to circular and data-driven practices because of its capacity to connect the digital and physical worlds.

3.3. Artificial Intelligence and Predictive Analytics for Smarter Decision-Making

Artificial Intelligence (AI) and predictive analytics are quickly coming to be recognized as compelling sets of data-driven methods for informing decision-making throughout coffee supply. IoT and blockchain may provide near-infinite amounts of historical and current data and events; but it is AI that make sense of all that. AI will now analyze vast datasets in real time, recognize patterns, identify inefficiencies, even forecast upcoming issues—allowing actors across the supply chain to move before problems arise rather than after. For instance, AI models are already forecasting crop yield from observed weather trends, detecting abnormal fermentation stages that could affect quality, and even predicting delivery routes with less carbon footprint and delivery time (Kamilaris et al., 2018). One of AI's key assets in this respect is its capacity to reveal "invisible" sources of waste and risk—root causes that may go unnoticed until the point of no return. Automation using transdisciplinary methodologies and forms of machine learning algorithms to examine input-output ratio metric sorting indexes at the processing stage can identify energy wasting, degraded roasting conditions affecting quality, and equipment functionality challenges. At the logistical level, and in supply chain scenarios, AI can monitor actual temperature data from sensor equipped containers and scour report data allowing it to recommend a more effective means of transport or storage condition determined to minimize spoilage. When employed reasonably consistently, these types of interventions will support minimizing waste and helpful recommendations and best practices for more efficient energy and water consumption, reflected in a minimize coffee production and distribution carbon footprint over time. Beyond the operational efficiencies, AI tools are also being employed to support sustainability assessment and certification. AI can aggregate data from several data sources—farms, cooperatives, exporter associations, and coffee retailers—and provide forms of automated information for sustainability scores and dashboards to indicate key performance indicators (KPIs) across the environment, social and economic pillars. This type of data sourcing and systems could also help brands better respond to consumer market demands for traceable and ethically sourced products by facilitating reporting and enhancing transparency. While there is promise, there may be specific pragmatic and ethical impediments to their uptake, particularly in the coffee sector. High development costs, the requirement of large, reliable datasets, and limited technical capacity among small producers are barriers to broad-based utilization and implementation. There are also concerns surrounding algorithmic bias and the possibility of not having smallholders in the decision-making process if AI tools are not developed with inclusion in mind. That said, AI and predictive analytics can allow the coffee supply chain to move away from a reactive system and work more data-informed, anticipate actions, and move more efficiently when it is applied appropriately. AI and predictive analytics turn data into insight – and insight into action – all with the aim of supporting a more intelligent, responsive, and sustainable coffee economy.

3.4. Mobile Applications and Farmer-Centric Platforms for Inclusive Traceability

Mobile technologies are becoming increasingly vital in bridging the digital divide between coffee producers on small farms and the broader supply chain. While many emerging technologies (e.g., blockchain, AI) may involve a sophisticated and complex infrastructural context, mobile applications generally provide a more accessible entry point to digitization—especially in rural and low-resource environments. Most mobile technology-based platforms are designed to be utilized by farmers, cooperatives, or field agents (e.g., those who work directly with farmers) for identification of recordkeeping and documenting planting timing, pesticide use, harvesting volumes, and certification status, as well as accessing training resources, and sharing data that support traceability and sustainability goals (Ribeiro et al., 2020).

One of the most valuable features of mobile apps in this area is how they readily support accurate recordkeeping. For example, through their smart phones alone, farmers can record the date of planting, amount and types of pesticides used, volume harvested, certification status, etc. The act of completing documentation feeds into a system of traceability; but it may also help smallholders make more informed decisions about their own business. Also, sometimes these apps enable farmers to have an asynchronous form of dialogue with buyers or certifiers—thereby making verification easier and improving trust within the supply chain. In addition to traceability, mobile platforms can also provide other services which can provide access to weather forecasts, market prices, financial services, and sustainability training modules. These services are essential to help build resilience in smallholders. For example, if an app informs farmers about changing rainfall patterns, it may help them to adjust their planting schedules or mitigate potential disease outbreaks. Further, if a farmer receives a price update, they can negotiate more equally and fairly with intermediaries about prices. In situations where formal traceability systems are still being developed, mobile-based applications provide a viable, scalable solution to include producers in a digital ecosystem, as it often doesn't require additional infrastructure. When mobile applications are able to aggregate their data with large scale platforms, such as the ones that use sensors, blockchain systems, or AI type tools, it can assure that even the smallest coffee player can be seen, and contribute to a sustainability

monitoring system. However, these tools cannot be utilized and useful in the field without more investment in training, language localization, and offline functionality. Also, digital literacy issues, data privacy, and equitable access need to be addressed to avoid contributing to existing inequalities in the supply chain. The rise of mobile farmer platforms nonetheless signals a broad shift toward participatory traceability, where the people cultivating the coffee are no longer just being studied but are being empowered to co-create what sustainability looks like and how it is measured. When inclusive design principles are applied to these tools, they can strengthen farmer voice, ensure data integrity and, ultimately, support a more connected, transparent and equitable coffee supply chain.

3.5. Integrated Platforms and Decision Support Systems (DSS) for Holistic Sustainability Management

Although specific technologies such as blockchain, IoT, and mobile apps create high value in different sections of the coffee supply chain, the true benefits/disruptive potential of these technologies comes when they are integrated into a digital ecosystem. Integrated digital platforms—often called decision support systems (DSS)—serve as centralized integration points that can connect a range of data points across the entire value chain. This will allow for real-time tracking, sustainability assessment, and data-driven decision-making in an easy-to-understand manner for the various stakeholders by visualizing complex information in rich dashboards (Beverungen et al., 2020; Verdouw et al., 2021).

In practical terms, these systems integrate data from sensor networks, traceability applications, blockchain ledgers, and satellite monitoring systems to create a coherent view across the supply chain. For example, a cooperative manager can use a Decision Support System (DSS) to track which producers are meeting sustainability thresholds, pinpoint any waste or inefficiencies, or assess compliance with environmental or social standards. The same platform can be used by processors to investigate energy and water use, discover equipment inefficiencies, or organizing roasting operations to minimize environmental impact (Kaloxylos et al., 2014; Wolfert et al., 2017). This level of integrated decision-making benefits not only streamlined operations, but also compliance with growing national and international standards for sustainability. One of the key advantages of these systems is their interoperability(ability to link to external databases, certification systems, and even public policy portals). Their automated data syncing and standardized formats can help reduce administrative burdens for producers and enhance accuracy and transparency of reporting (França et al. 2020). They also allow actors in the supply chain to model a range of sustainability scenarios — such as capital investment into renewable energy sources or circular ways to handle waste — and ultimately project the impact of their proposed change before it is implemented giving better risk management and improved efficiency of investment (Tsolakis et al. 2014). Some 'next generation' systems are now embedding elements of machine learning & artificial intelligence to constantly improve their forecasting capacities. For instance, some are using predictive maintenance algorithms to highlight slow-fail-ure from a potential equipment failure, or by using environmental forecasting tools/machine learning tools to suggest changes in harvest or shipping schedules, as the weather starts to shift (Kamilaris et al., 2017). Such advancements help to accommodate a more proactive, anticipatory supply chain management mode. Yet, in order to obtain the benefits of these integrated systems requires investment in digital infrastructure, data literacy, and institutional capacity—especially in the upstream sections of chain behaviour systems where many smallholder farmers are involved. Inclusive design practices and policy structures have to manage data ownership opportunities, cybersecurity, and equitable group access. While these challenges exist, integrated digital platforms and DSS are a fundamental approach to creating better systems of smart, accountable, and sustainable coffee production. By creating meaningful insight from data, and decision making can be done faster, across all areas of the supply chain—ensuring sustainability is measured and controlled rather than simply reporting on sustainability. To address the fragmentation of digital tools and better facilitate systemic transformation, this study proposes a conceptual framework in which the Decision Support System (DSS) acts as a central integration hub. The DSS aggregates data streams from Blockchain (traceability and transaction history), IoT devices (real-time monitoring), AI models (predictive analytics), and Mobile applications (field-level data input from farmers and cooperatives). These data streams are synchronized into a unified dashboard that enables comprehensive sustainability assessment and operational decision-making. For example, IoT sensors track humidity levels in shipping containers, Blockchain ensures the traceability and compliance logs, while AI interprets patterns to forecast spoilage risks. Mobile apps allow stakeholders to upload or verify data in real time. The DSS translates these combined inputs into actionable insights—flagging inefficiencies, visualizing KPI trends, and recommending waste valorization or resource optimization interventions. This integrated ecosystem enhances transparency, responsiveness, and cross-actor coordination in the coffee supply chain.

3.6. Comprehensive Assessment Framework: Introducing Key Indicators for Evaluating Sustainability in the Coffee Supply Chain through surveys

To comprehensively assess the sustainability of the coffee supply chain, a diverse array of factors spanning social, economic, and environmental domains must be considered. These factors serve as critical touchpoints for understanding the intricate dynamics of coffee production, distribution, and consumption. Social indicators delve into labor practices, community engagement, and workers' rights, shedding light on the human aspect of the supply chain. Economic indicators explore income distribution, market access, and financial transparency, offering insights into the economic viability and equity within the system. Environmental indicators

probe into sustainable farming practices, waste management, and biodiversity conservation, reflecting efforts to minimize ecological footprints and preserve natural resources. Together, these indicators provide a holistic framework for evaluating the sustainability performance of the coffee supply chain, guiding stakeholders towards informed decision-making and targeted interventions. The forthcoming table presents a detailed compilation of these indicators, delineating their respective variables and sub-variables to facilitate comprehensive assessment and analysis. The table below represents the possible indicators and variables to conduct the survey on the coffee supply chain sustainability (Table 1). Moreover, the annex includes more details such as the sub variables for each variable (Appendix A).

The Coffee Supply Chain Sustainability Questionnaire is designed to collect comprehensive information on sustainability practices from various stakeholders involved in the coffee industry, including growers, processors, exporters, importers, roasters, retailers, consumers, NGOs, governmental bodies, and academic institutions. The questionnaire encompasses a wide range of topics, including demographic information, current environmental, social, and economic sustainability practices, challenges and barriers to implementing these practices, motivations and opportunities for improvement, and the use of certifications and sustainability standards. It also includes questions about logistics, quality control, and consumer preferences, as well as the potential benefits and challenges of implementing the Physical Internet concept to enhance efficiency and sustainability. This diverse array of questions (closed-ended with Likert scale and Yes or No questions and open-ended questions) aims to provide a holistic understanding of the sustainability landscape within the coffee supply chain. To ensure real-world applicability, each indicator in the proposed framework can be measured using a combination of quantitative and qualitative methods. Data sources may include farm-level records (via mobile apps), IoT sensor outputs (e.g., energy use, waste quantities), blockchain-based traceability logs (e.g., transaction timestamps, origin data), and external reports from certifiers or cooperatives. Responsibility for data collection would vary by stakeholder group—for instance, farmers and cooperatives for production-related indicators, processors and exporters for quality control and resource efficiency, and NGOs or certification bodies for labor practices and social engagement. In contexts where direct data is unavailable, proxy indicators (such as participation in certification schemes or use of sustainable inputs) could be used to infer performance. This approach allows for flexible yet rigorous monitoring across diverse geographies and operational scales.

Table 1: indicators and variables list for the characterization, analysis and mapping of coffee supply chain

Indicators	Variables
Social sustainability	Labor practices of coffee
	Community impact
	Diversity and inclusion
	Health and safety
	Workers' rights in the coffee sc
	Community engagement
Economic sustainability	Economic impact on coffee producers
	Value chain distribution
	Market access and pricing
	Economic resilience strategies
	Market access initiatives
	Financial impact of sustainable practices
Environmental sustainability	Sustainable coffee farming practices
	Coffee waste management
	Carbon footprint (for consumption or farming or transofmring)
	Resource efficiency
	Conservation of biodiversity
	Unutilized coffee waste

4. Conclusion

Persistent inefficiencies, fragmented data, and poor waste valorization continue to challenge the sustainability of the global coffee supply chain. Every year, millions of tons of spent grounds, husks, and defective beans are discarded—wasted resources that could be repurposed. This study highlights how digital technologies and well-defined sustainability indicators can transform the sector by enhancing waste governance and traceability.

Through systematic analysis of academic research, policy documents, and technological practices, we identified core weaknesses in traceability systems—resulting in inefficient resource recovery, certification bottlenecks, and quality losses. However, technologies like blockchain, IoT, AI, and mobile platforms offer viable solutions to these challenges by enabling real-time data sharing, automated compliance checks, and transparent interactions between supply chain actors.

One major contribution of this work is the development of a sustainability indicator framework structured across three dimensions: environmental, economic, and social. This tool allows for practical assessment and guides intervention points via Decision Support Systems (DSS), helping shape better strategies and policies.

We propose four key recommendations:

1. **Invest in digital infrastructure and capacity building**, especially for smallholder farmers and cooperatives.
2. **Foster policy alignment and multi-stakeholder collaboration** to standardize data, ensure privacy, and support public-good tech initiatives.
3. **Expand research on equity and inclusion** to ensure digital tools address—not reinforce—existing power asymmetries.
4. **Encourage waste valorization ecosystems** that create new revenue streams through the reuse of coffee by-products.

Ultimately, sustainability in the coffee sector requires more than incremental improvements. It calls for a systemic transformation driven by integrated technologies, inclusive governance, and bold investment in future-ready infrastructure.

- **Acknowledgement**

We acknowledge financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, Call for tender No. 104 published on 2.2.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU– Project Title PRISMA Platform (Physical internet RegeneratIve Sustainable MAterials) – CUP I53D23001660006 - Grant Assignment Decree No. 961 adopted on 30/June/2023 by the Italian Ministry of Ministry of University and Research (MUR).

References

Bager, S.L., Lambin, E.F. and Meyfroidt, P., 2021. Sustainability strategies by companies in the global coffee sector. *Business Strategy and the Environment*, 30(7), pp.3055–3072. https://doi.org/10.1002/bse.2787

Beverungen, D., Müller, O., Matzner, M., Mendling, J. and vom Brocke, J., 2020. Conceptualizing smart service systems. *Electronic Markets*, 30, pp.23–47.

Brewster, C., Roussaki, I., Kalatzis, N., Doolin, K. and Ellis, K., 2017. IoT in agriculture: Designing a Europe-wide large-scale pilot. *IEEE Communications Magazine*, 55(9), pp.26–33. https://doi.org/10.1109/MCOM.2017.1600528CM

FAO, 2019. *Digital technologies in agriculture and rural areas – Briefing paper*. Food and Agriculture Organization of the United Nations.

França, C.L., Broman, G., Robèrt, K.H., Basile, G. and Trygg, L., 2020. An approach to business model innovation and design for strategic sustainable development. *Journal of Cleaner Production*, 140, pp.155–166.

Galvez, J.F., Mejuto, J.C. and Simal-Gandara, J., 2018. Future challenges on the use of blockchain for food traceability analysis. *Trends in Analytical Chemistry*, 107, pp.222–232. https://doi.org/10.1016/j.trac.2018.08.011

GRI, 2021. *Consolidated Set of GRI Sustainability Reporting Standards 2021*. Global Reporting Initiative.

ICO, 2021. *Coffee Development Report 2021: The Future of Coffee – Investing in Youth for a Resilient and Sustainable Coffee Sector*. International Coffee Organization.

Kaloxylos, A., Wolfert, S., Verwaart, T. et al., 2014. The cloud of things for agricultural value chains. *Journal of Smart Agricultural Technology*, 16, pp.58–70. https://doi.org/10.1016/j.compag.2014.03.001

Kamilaris, A., Fonts, A. and Prenafeta-Boldú, F.X., 2017. The rise of blockchain technology in agriculture and food supply chains. *Trends in Food Science & Technology*, 91, pp.640–652.

Kamilaris, A., Prenafeta-Boldú, F.X. and Fonts, A., 2018. A review of the use of artificial intelligence in agriculture. *AI in Agriculture*, 1, pp.1–11. https://doi.org/10.1016/j.aiia.2019.01.001

Lin, J., Shen, Z., Zhang, A. and Chai, Y., 2017. Blockchain and IoT-based food traceability for smart agriculture. *Proceedings of the 3rd International Conference on Crowd Science and Engineering*, pp.1–6. https://doi.org/10.1145/3126973.3126980

Ribeiro, M., Walter, A., do Amaral, W.R. and Soares, S.R., 2020. Digital agriculture and mobile applications: Tools for sustainable development in the coffee sector. *Journal of Cleaner Production*, 273, 122885. https://doi.org/10.1016/j.jclepro.2020.122885

Samper, L.F. and Quiñones-Ruiz, X.F., 2017. Towards a balanced sustainability vision for the coffee industry. *Resources*, 6(2), p.17.

Tian, F., 2016. An agri-food supply chain traceability system for China based on RFID & blockchain technology. *13th International Conference on Service Systems and Service Management (ICSSSM)*, pp.1–6. https://doi.org/10.1109/ICSSSM.2016.7538424

Tsolakis, N., Srai, J.S., Kumar, M. and Graham, G., 2014. Impact of product variety on sustainable supply chain network design. *International Journal of Production Economics*, 157,pp.451–467. https://doi.org/10.1016/j.ijpe.2013.11.021

UNEP, 2020. *Sustainability and Circularity in the Textile Value Chain: A Global Roadmap*. United Nations Environment Programme.

Verdouw, C.N., Kruize, J.W. and Wolfert, J., 2021. Digital twins in smart farming. *Agricultural Systems*, 189, 103046.

Verdouw, C.N., Wolfert, J., Beulens, A.J.M. and Rialland, A., 2016. Virtualization of food supply chains with the internet of things. *Journal of Food Engineering*, 176, pp.128–136.

Wolfert, S., Ge, L., Verdouw, C. and Bogaardt, M.J., 2017. Big Data in Smart Farming – A review. *Agricultural Systems*, 153,pp.69–80.

APPENDIX A. LIST OF SUB VARIABLES INCLUDED TO CONDUCT THE SURVEY ON COFFEE SUPPLY CHAIN SUSTAINABILITY

Indicator	Variables	Sub-variables
Social	Labor Practices	Percentage of workers receiving fair wages
		Compliance with fair labor standards
		Availability and utilization of healthcare benefits
	Community Impact	Investment in community development projects
		Contributions to local education initiatives
		Support for healthcare programs in local communities
	Diversity and Inclusion	Diversity statistics in the workforce
		Gender equality initiatives
		Inclusive hiring practices
	Health and Safety	Adherence to safety protocols in coffee production
		Frequency of health check-ups for workers
		Availability of personal protective equipment
	Workers' Rights	Awareness levels of workers' rights
		Existence of grievance mechanisms for workers:
		Accessibility and effectiveness of communication channel for workers
	Community Engagement	Frequency and scope of community forums and consultations
		Collaboration in community projects and initiatives
		Financial contributions to community development
Economic	Economic Impact on Producers	Income of Coffee Farmers
		Access to Market Information:
		Profitability of Coffee Farming
	Value Chain Distribution	Fair Distribution of Profits
		Economic Benefits for Intermediaries
		Financial Transparency
	Market Access and Pricing	Market Access Initiatives
		Pricing Mechanisms
		Impact of Market Fluctuations
	Economic Resilience	Diversification of Income Sources
		Adaptation to Market Trends
Economic	Market Access Initiative	Certifications and Quality Standards
		Market Development Programs
		Collaboration with Retailers
	Financial Impact of Sustainable Practices	Costs and Benefits of Sustainable Practices
		Return on Investment in Sustainability
		Access to Sustainable Markets
Environmental	Sustainable Farming Practices	Organic Farming Certification
		Water Conservation Measures
		Biodiversity Preservation
	Waste Management	Coffee Pulp Utilization
		Recycling Initiatives
		Reduction of Single-Use Plastics
	Carbon Footprint	Carbon Emission Reduction Initiatives
		Transportation Efficiency
		Energy Consumption Reduction
	Resource Efficiency	Water Usage Efficiency
		Energy-Saving Practices
		Land Management for Sustainability
	Conservation of Biodiversity	Agroforestry Practices
		Wildlife Habitat Preservation
		Use of Shade-Grown Coffee
	Unutilized Coffee Waste	Disposal Practices for Unutilized Coffee
		Repurposing Unutilized Coffee
		Reduction of Unutilized Coffee Waste