

Identification of the potential contribution of the physical Internet to the issues and challenges of the coffee supply chain in Ethiopia.

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Abstract: *Our article explores the challenges and problems associated with managing the coffee supply chain in developing countries and examines how the physical Internet can solve them. To do this, we look at the case of the Ethiopian coffee supply chain. By leveraging hyperconnected logistics, multimodal transport and digital supply chain solutions, we highlight opportunities to improve economic, environmental and societal sustainability. Our literature review identifies key barriers such as supply chain fragmentation, lack of real-time visibility and inefficient transport and storage. We propose that the principles of the physical Internet should be harnessed to improve traceability, reduce waste and promote fair trade, particularly in the coffee supply chain, where they have not been used before. This research contributes to the wider debate on sustainable, resilient and inclusive global supply chains.*

Keywords: *Physical Internet, Coffee Supply chain, Supply Chain Management, Developing countries, Food supply chain, Collaboration, Sustainability.*

Physical Internet (PI) Roadmap Fitness: *Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), Transportation Equipment, PI Networks, System of Logistics Networks, Vertical Supply Consolidation, Horizontal Supply Chain Alignment, Logistics/Commercial Data Platform, Access and Adoption, Governance.*

Targeted Delivery Mode-s: Paper, Poster, Flash Video, In-Person presentation

1 Introduction

From a logistics perspective, the coffee supply chain is a major topic as it is not only the second most consumed beverage in the world, but also the second most traded commodity after oil (Murthy & Madhava Naidu, 2012). As a result, there are huge flows of coffee-related products, data and information around the world. In the global coffee supply chain, Ethiopia, known for its specialty coffee varieties, is the seventh largest contributor to coffee exports (Capital Newspaper, 2023).

Coffee is a fruit - a kind of cherry. Like many fruits, it has an outer skin under which is the pulp or flesh of the fruit, and then a seed inside, wrapped in different types of layers. There are

various ways of processing coffee to remove the different layers to obtain the coffee bean, which is then roasted and ground to produce a coffee ready for brewing.

Understanding these processes is key to identifying logistical inefficiencies and process misalignments in the supply chain. There are two types of processes in the Ethiopian coffee supply chain. (Tadesse, 2024) has mapped the processes and actors in the supply chain (Figures 1 and 2). The Ethiopian coffee supply chain from farm to export involves many actors with overlapping roles, uncertainties and disruptions that affect the supply chain, and constantly changing government regulations. This makes the Ethiopian coffee supply chain very complex and gives rise to a series of problems and/or difficulties.

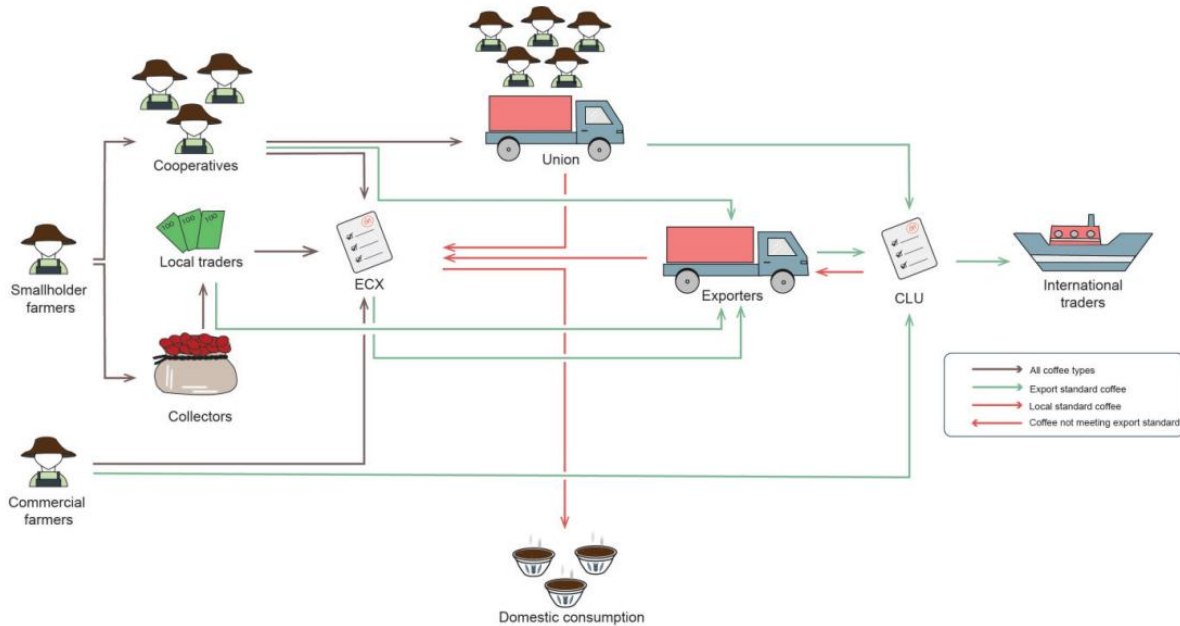


Figure 1: The Ethiopian coffee supply chain (ECX: Ethiopian Commodity Exchange, CLU: Coffee Liquoring Unit)(Tadesse, 2024).

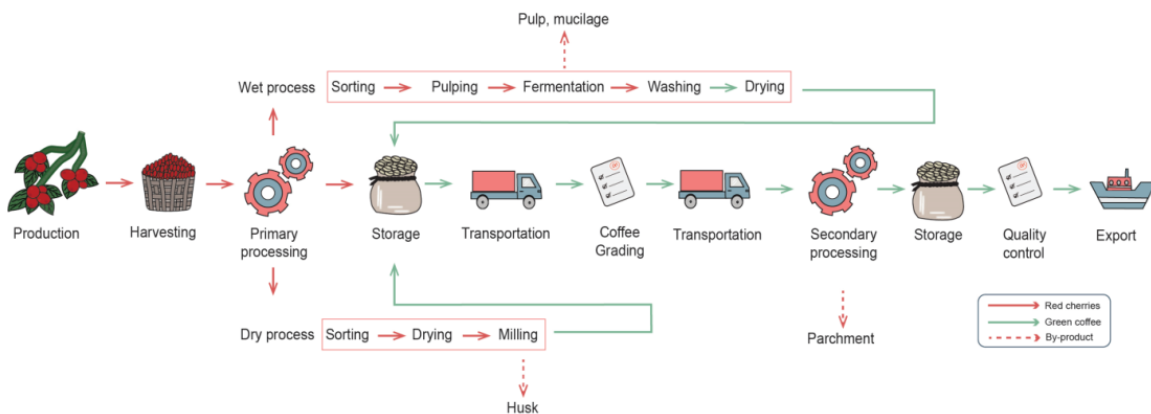


Figure 2: Logistics activities in the coffee supply chain for the export (Tadesse, 2024).

One of the main objectives of this research work is to identify the supply chain issues concerning Ethiopian coffee and to assess their similarities with the challenges posed by several global supply chains. Our objective is to assess the possibility of leveraging conceptual frameworks and innovations used in other supply chains to solve or mitigate the Ethiopian supply chain problems. In particular, the Physical Internet (PI), first introduced by (Montreuil, 2011), has attracted a great deal of research interest over the last decade, especially in relation to the challenge of global sustainability. As a result, solutions to various theoretical and applied supply chain problems are constantly being developed within PI (Matusiewicz, 2024).

However, its application to coffee supply chain problems has not yet been studied. This is why we first wanted to study the extent to which the physical Internet (PI) could be used to solve the problems of the Ethiopian coffee supply chain.

This article is structured as follows. Section 2 describes the methodology. In section 3, we summarize the challenges we have identified in the supply chain. A mapping of Physical Internet capabilities that can be exploited to address the challenges in the coffee supply chain is then presented in section 4. Section 5 then discusses the importance of applying PF in the supply chain of a developing country such as Ethiopian coffee and the associated challenges that need to be addressed. Finally, section 6 concludes with the main findings and research perspectives.

2 Methodology

To answer the research question about the applicability of PI to the Ethiopian coffee supply chain, the following methodology was followed. First, a stakeholder interview is conducted to get deep insights into the problems of the Ethiopian coffee supply chain. The number and profiles of interviewees is presented in Table 1.

Table 1: Interviewee profiles

Supply chain actor	Number interviewed
Local Exporter	3
International trader	2
Artisan café owners affiliated with specific coffee farms	4
Representatives of associations of coffee traders	3
Representatives of coffee trading unions	1
Total number of Interviews	13

The interview notes were then compiled and summarized into major clusters which are presented in section 3. This is followed by formulation of a set of keywords associated with the clusters of problems identified. By combining these keywords with the terms coffee supply chain and Physical Internet and PI, a set of literature search queries was formed. These queries were plugged into the research database Web of Sciences to yield a combined set of 173 articles.

Upon close examination and thorough reading, after careful scrutiny and extensive reading, a set of papers deemed relevant to the research question was selected. A total of 48 articles were selected for this article, including 10 general reference articles.

3 Key Supply chain Challenges Identified

The interview notes distill to the category of supply chain problems below. Where available, corroborations from literature are also presented.

- a) *Infrastructure inefficiencies*: facilities such as warehouses, de-pulping and washing stations as well as testing laboratories are used sub-optimally, as manifested in:
- Overcrowding of some warehouses while others are underloaded;
 - Lack of transport fleets while transport service is available in the capacity pool;
 - Queues at de-pulping and hulling stations, as well as quality testing laboratories;
 - Specialized facilities are not well equipped for their intended use, in terms of housing the right set of milling, washing, sorting and handling equipment. Human labor is also used extensively in handling tasks, which reduces efficiency;

- Planning of the layout within large facilities is not done with operational optimality in consideration, which also increases inefficiency.
- b) *Lack of Information sharing among stakeholders*: Not all stakeholders have up-to-date information on available stocks and transport services, which limits choice and can lead to sub-optimal decisions. Access to technology, difficulty of implementation in terms of skilled labour, cost of implementation and resistance from stakeholders are all challenges to obtaining information. This is also corroborated by (Tadesse *et al.*, 2024).
- c) *Market demand and price volatility*: There is high variability in international demand for coffee. As corroborated by (Worako *et al.*, 2011), the Ethiopian coffee supply chain is affected by high price volatilities.
- d) *Climate change risks*: A majority of the Ethiopian Coffee is harvested from small-holder farms. These farms are closely linked to some of the oldest natural forests in Ethiopia (Davis *et al.*, 2018). The forests are vulnerable to several effects of climate change and human activities such as deforestation.
- e) *Logistics cost fluctuations*: There are significant volatilities in logistics costs. Causes contributing to these fluctuations include, but are not limited to: lack of information on available supply of transportation and inventory services leading to speculative pricing and/or oligopoly, presence of information brokers between actors of the supply chain, political and/or security instabilities.
- f) *Disruptions to operational continuity*: The coffee supply chain is vulnerable to disruption of flows. Interviewees have stated a number of risks in this regard including:
 - Security issues;
 - Theft of coffee: a significant number of instances for the theft of coffee are reported by anonymous sources (Bogale, 2023); there is also a market for a local trading of export-standard coffee as reported by (Metekia, 2022);
 - Transport infrastructure problems: the Ethiopian rural road network is vulnerable to weather effects; e.g., landslides which block key arterials of the road network are common during rainfall seasons.
- g) *Regulatory uncertainty*: The policies and regulations governing the coffee supply chain in Ethiopia had not been largely based on evidence; rather, they have been highly dependent upon the incumbent government's political priorities throughout the years (Mas Aparisi, 2024).
- h) *Data Scarcity*: the existing data repositories are incomplete in many forms including temporal continuity, spatial coverage and type of data collected in terms of giving a full picture of the supply chain.
- i) *Packaging and handling problems*. Coffee is very sensitive to environmental conditions in terms of temperature, humidity and chemicals. However, packaging is widely done using 60Kg pockets which are then stacked and containerized for shipping. The issues related to this process are:
 - *Standardization and quality*: There is neither an accepted standard for the 60Kg bags nor a list of approved suppliers for the bags. This means exporters are sourcing these bags from all available suppliers to meet order timelines. Such practice may lead to procuring packaging that can potentially harm the coffee quality in terms of its chemical content or in preserving the coffee;
 - *Ample supply of bags*: There isn't a cultivated local capacity to produce bags that are sufficient for the export volume of coffee. Furthermore, it has reliability issues regarding meeting orders on time. Although the exact problems of the

logistics of 60Kg bags needs to be investigated further, inadequate supply of bags is a topic that has been present in interviews;

- Handling of coffee in warehouses, mills and during transportation is not under carefully controlled conditions. This can potentially incur reduced pricing and/or rejection of the coffee from export markets.

After careful examination of the above problems, the authors hypothesize that the physical internet can offer a viable set of solutions to some of the problems above. Accordingly, the section below presents a review of literature linking the physical internet concept to problems similar to the above problems in the coffee supply chain.

4 Mapping Physical Internet Capabilities to Coffee Supply Chain Challenges

To find evidence supporting the hypothesis, we devise the following set of queries consisting of keywords derived from the problem in section 3:

- Efficiency & Optimization: TITLE: *Physical internet*; AND ABSTRACT: "*efficien**" OR "*inefficien**" OR "*optim**" OR "*perform**" OR "*utilization*" OR "*resource**" OR "*facilit**" OR "*productivity*" OR "*inventory*" OR "*infrastructure*"
- Uncertainty or volatility: TITLE: *Physical internet* AND ABSTRACT: "*uncertain**" OR "*volatil**" OR "*instabil**" OR "*variab**" "*risk*" OR "*unpredictab**" OR "*requirement**" OR "*data need**" OR "*lack of data*" OR "*inaccurate data*" OR "*erroneous data*" OR "*uncertain data*" OR "*data reliability*" OR "*unreliable data*" OR "*trace**"
- Quality & Packaging: TITLE: *Physical internet* AND ABSTRACT: "*quality*" OR "*pack**" OR "*sensitive material*" OR "*perishable*"

Table 2: Examples of PI solutions with their degree of maturity that could be used to solve problems in the coffee supply chain

Problem	PI Solutions			
	Conceptual framework	Algorithms & Simulation models	PI prototypes & IT infrastructure	Operational System
Inefficient utilization of resources	(Adamczak <i>et al.</i> , 2018)	(Chen <i>et al.</i> , 2018)		
Poor logistics infrastructure	(Tran-Dang & Kim, 2018)	(Dang Hoa & Kim, 2018)	(Osmólski <i>et al.</i> , 2019)	
Uncertainty, volatility & disruptions	(El Ouadi <i>et al.</i> , 2021)	(Yang <i>et al.</i> , 2017)		(Achamrah <i>et al.</i> , 2024)
Regulatory & policy environment	(Moshood & Sorooshian, 2021)	(Lemmens <i>et al.</i> , 2019)		

Scarcity and Inaccuracy of Data	(Sun <i>et al.</i> , 2024)			
Quality and traceability	(Hasan <i>et al.</i> , 2021)	(Chen <i>et al.</i> , 2018)	(Lin & Cheng, 2018)	
Ecological impact & sustainable development	(Puskás & Bohács, 2021)	(Chen <i>et al.</i> , 2018)		

Upon inserting these queries were plugged into the research database Web of Sciences we got a total of 173 articles. Among these we selected 146 for further reading, based on their relevance to the research question. These articles were thoroughly reviewed in a second-round review and mapped according to their relevance to similar problems in the coffee supply chain.

The mapping was further refined to 38 articles as given in Table 2.

Table 2 illustrates some of the capabilities of PI to address challenges similar to those in the Ethiopian coffee supply chain that we have identified through our more comprehensive literature review.

Looking at PI's contribution to each challenge separately, we envisage the following opportunities:

- a) *Inefficient Utilization of Resources*: PI can be leveraged to optimize resources in transportation, handling and inventory areas through open-access logistics networks and AI-driven planning. Storage space in trucks can be maximized using the differently sized modular boxes belonging to different shipping actors. This also reduces empty returns maximizing potential for dual export and local markets. The real-time response and coordinating capabilities of PI can be utilized to coordinate coffee shipments from farming areas like Kaffa to Addis Ababa, ensuring full truckloads and shared routes among cooperatives.
- b) *Poor Logistics Infrastructure*: Unpaved rural roads and sub-optimal Ethiopian Commodity Exchange (ECX) hubs, hamper coffee transport and storage, especially during rainy seasons. The Physical Internet can introduce modular, scalable infrastructure designed for resilience. Sensor-equipped standardized containers and trucks able to navigate more rugged terrain can be leveraged to reduce dependence on advanced roads. PI can also offer upgrading frameworks for warehouses, auction centers and hubs to replace or upgrade ECX facilities. Using the tropical sun, which Ethiopia has ample of, a significant proportion of energy requirements could be fulfilled without waiting for full rural electrification.
- c) *Uncertainty, Volatility & Disruptions*: Challenges like weather disruptions, market price swings, and operational disruptions can be met by PI through predictive analytics and real-time adaptability. Data platforms integrate historical and live data (e.g., weather, market trends) to forecast disruptions and optimize routes. For instance, if rains block a rural road, PI systems can reroute coffee via alternative hubs, minimizing delays. Applications such as blockchain can enable traceability, ensure contract stability and reduce potential price volatility that impacts farmers.
- d) *Regulatory & Policy Environment*: Ethiopia's regulatory environment lacks evidence-based policy frameworks for digital logistics, data security, and industrial collaboration, slowing innovation in the coffee sector. PI requires and promotes policy evolution by necessitating standardized protocols that align stakeholders. PI's implementation can

- drive government action to enact laws for container standards, cyber-physical security of infrastructure, and cross-border trade, fostering public-private partnerships.
- e) *Scarcity and Inaccuracy of Data*: Limited and inaccurate data on yields, quality, and logistics in Ethiopia's coffee supply chain hinders planning and transparency. There is an immense opportunity to extract vast quantities and different kinds of data on the coffee supply chain by deploying IoT sensors and shared data platforms to collect real-time, accurate information across the supply chain. PI's open-access networks enable farmers, cooperatives, and exporters to contribute and access data on production volumes, transport status, and market needs. For instance, sensors on PI containers could track coffee starting from Yirgacheffe farms to the Djibouti port, feeding a stream of data to cloud platform that corrects yield estimates.
 - f) *Quality and Traceability*: PI can very well be used to meet coffee's quality sensitivity and need of precise handling. PI enhances quality and traceability through smart containers equipped with sensors monitoring variables like moisture and temperature, tailored to Ethiopian coffee's needs. PI's blockchain-based platforms can secure end-to-end traceability, recording each step from farm to export, verifiable by buyers. This firmly establishes market trust and sustainable revenue.
 - g) *Ecological Impact & Sustainable Development*: Ethiopian coffee is largely produced by small-holder farms, which are ecologically connected to some of the oldest natural forests, in a natural manner without fertilizer additions to the soil (Davis *et al.*, 2018). These facts render the Ethiopian coffee supply chain one of the greenest export industries in Ethiopia. PI can build on this further by drawing power from Ethiopia's green electricity generated from hydropower (International Trade Administration, 2024). This will strengthen the strategic sustainability of the coffee supply chain.

5 Discussion: Challenges & Feasibility of PI Implementation in Ethiopia

The reviewed literature shows the potency of PI to solve the coffee supply chain's problems. However, we see that there are barriers to be overcome in the Ethiopian coffee supply chain and in supply chains in developing countries at large, before PI can be implemented. These are detailed below.

1. Technological Barriers

- **Unreliable Communication Networks**: Limited network reliability and availability hinder real-time data sharing, reducing PI's responsiveness and traceability capabilities critical for coffee quality monitoring.
- **Lack of Localized Solutions**: Developing PI-specific technologies, such as innovative containers from local materials, affordable wireless sensor networks, and quality-monitoring systems tailored to coffee's sensitivity (e.g., moisture, temperature), remains a scientific and technical challenge.
- **High Adoption Costs**: Implementing PI requires substantial investment in infrastructure (e.g., IoT sensors, cloud platforms), trained specialists, and farmer acclimatization, posing financial challenges for small-scale producers and cooperatives.

2. Policy and Regulatory Gaps

- **Lack of PI Frameworks**: Ethiopia lacks policies for PI standardization, data security, and cross-departmental coordination, impeding collaboration between universities, industry, and government for sustainable logistics.
- **Insufficient Incentives**: Limited government funding, trade barrier reforms, and labor laws to mitigate Industry 4.0 job losses discourage private sector investment in PI technologies.

- Leadership Deficit: Without proactive government leadership in digital platforms, cybersecurity, and skilled labor development, PI implementation lacks the regulatory push needed for stakeholder alignment.

3. Trust and Data Sharing Issues

- Stakeholder Reluctance: Smallholder farmers and other actors hesitate to share data (e.g., yields, pricing) in a perceived low-trust environment, fearing exploitation or competitive disadvantage.
- Inadequate Data Practices: The absence of robust data collection and sharing systems limits supply chain visibility, hindering PI's ability to optimize processes and predict disruptions.
- Collaboration Challenges: Demonstrating PI's global benefits (e.g., higher profits) to individual companies and developing minimal-data-sharing methods to encourage participation remain critical hurdles.

4. Infrastructure Limitations

- Underdeveloped Logistics Hubs: Ethiopian Commodity Exchange (ECX) hubs, serving multiple roles (grading, storage, auctions), are bottlenecks due to limited facilities, requiring upgrades for PI's modular, efficient operations.
- Lack of PI-Compatible Systems: Current infrastructure, like 60-kg sacks and manual tracking, doesn't support PI's standardized containers, truck-trailer coupling, or real-time logistics planning.
- Energy and Sustainability Gaps: Unreliable energy supply constrains PI's sensor and communication arrays, while unstudied energy-coffee process relationships and unquantified CO₂ costs complicate justifying sustainable PI investments.

In various time horizons, several types of interventions are required to realize PI in the coffee supply chain. In the short term, we see the feasibility of pilot interventions including modernizing the transportation, handling, and warehousing of coffee; optimal design of facilities and processes, routing protocols and human resource management tools that minimize delays.

Setting up a national data platform for research, development and business endeavors can have a significant effect in the medium term. Another area is the incremental alignment of governance structure to reflect a shift to PI. This alignment involves the training of personnel across different government departments (e.g., customs, transport-related authorities, agriculture-related authorities, etc.), and supply chain actors.

Several long-term interventions are required to successfully embed the Physical Internet in the coffee supply chain. These include:

- strong investment into rural electrification and communications infrastructure while scaling digital literacy programs and wireless sensor networks to achieve seamless technological integration.
- improving the national data platform and strengthening trust through demonstration of business models that promote equitable profits for farmers, exporters, and international buyers, leveraging global partnerships for shared gains.
- establishing a national PI authority to formulate a robust legal framework that is locally relevant and globally compatible at the same time. A robust legal framework, led by a national PI authority, can enforce global-compatible standards and cybersecurity, resolving policy gaps.

6 Conclusion and Future Work

Through meticulous interviews and literature review, the key problems in the Ethiopian coffee supply chain have been identified. These are inefficiency and underdevelopment of

infrastructure, lack of data and a low-trust environment where data isn't shared among supply chain actors, uncertainties of policies which are often not evidence-based and technological barriers.

The consideration of PI to solve these problems in the context of the coffee supply chain in developing countries is an originality. In this regard PI shows significant promise as a solution framework, as demonstrated in the volume of research work reviewed.

The full implementation of PI, however, is a formidable challenge as of now. In this regard, we have proposed an incremental approach over a long-time horizon to overcome the challenge.

Once fully realized, Ethiopia can leverage PI to rip the benefits of a sustainable coffee supply chain. Hence, future research work is essential in areas of the short, medium and long-term interventions indicated in the previous section. Some quick wins could be harvested in pilots for modeling and optimization of facilities, scheduling and transportation protocols. Locally made sustainable packaging and the supply chain of the packaging material itself is also an interesting research avenue filled with interesting questions. Urban logistics of locally sold coffee also has room for research on collaborative logistics involving farmers, retail stores, coffee shops and artisan cafes.

The authors seek to explore several optimization techniques and simulation models to tackle a selection of problems in the aforementioned areas in the future.

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