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Environmental, Social, and Economic Life Cycle Assessment of the Italian Coffee Supply Chain

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Mizna Rehman [1] , Antonella Petrillo [2] , Fabio De Felice [1]

1. Dipartimento di Ingegneria, Università degli Studi di Napoli "Parthenope", Napoli, ITA 2. Dipartimento di ingegneria, Università degli Studi di Napoli "Parthenope", Napoli, ITA

Corresponding author: Antonella Petrillo, a.petrillo@unicas.it

Abstract

The global coffee sector presents complex environmental, social, and economic challenges that necessitate comprehensive sustainability assessments. In this context, the present research advances conventional environmental Life Cycle Assessment (LCA) of coffee by integrating Social Life Cycle Assessment (S-LCA), economic evaluation, Natural Capital Accounting, and Analytic Network Process (ANP) modeling to perform a multidimensional sustainability analysis of the coffee value chain in the Italian market context. Building on previously published environmental LCA results which estimated total greenhouse gas emissions at 3.5 kg CO_2-eq per kilogram of roasted coffee, with potential reduction to 0.62 kg CO_2-eq via biogas valorization and organic inputs, this research incorporates social and economic performance indicators through ANP-weighted trade-off analysis to assess trade-offs across sustainability domains. Using a cradle-to-grave boundary and a functional unit of 1 kg roasted coffee, we apply the UNEP/SETAC S-LCA framework, ANP decision modeling in SuperDecisions v2.10, and value chain economic modeling to quantify worker welfare, income distribution, and smallholder equity under organic and conventional farming scenarios. Natural capital flows are evaluated using a qualitative-quantitative hybrid model, capturing impacts on soil integrity, water depletion, and biodiversity. Results indicate significant interdependencies and trade-offs between environmental efficiency, social risk, and economic resilience, underscoring the necessity for integrated sustainability frameworks in agricultural supply chains under climatic uncertainty.

Categories: Engineering Management, Environmental and Sustainable Engineering, Environmental Engineering and Sustainability
Keywords: environmental life cycle assessment, social life cycle assessment, economic life cycle assessment, natural capital valuation, ecosystem services assessment, multicriteria trade-off analysis, sustainable supply chain metrics

Introduction

Coffee is one of the most valuable globally traded commodities, with an annual production of over 10 million tons and a retail market exceeding USD 460 billion as of 2023 [1]. Italy, as a cultural and industrial hub of coffee consumption, ranked among the top six importers worldwide, with over 670,000 tons of green coffee imported in 2022 [2]. The Italian roasted coffee sector, consisting of over 800 small and medium-sized enterprises (SMEs), contributes more than EUR 5 billion to the national economy annually and employs approximately 14,000 individuals [3]. Yet, the environmental, social, and economic sustainability of this sector remains under intense scrutiny, particularly within the global supply chains dominated by conventional monoculture farming systems in tropical nations. Italy represents a particularly relevant case study due to its status as one of the world's largest coffee-consuming nations per capita of 5.6 kg/year , with a distinctive consumption model centered around espresso culture and a strong domestic roasting sector. The country imports over 500,000 tonnes of green coffee annually, and maintains a high-value domestic roasting sector that captures a significant share of the final retail price, estimated at EUR 20/kg for roasted coffee, compared to €1.50-€2.50/kg farmgate prices in producing countries. This structure concentrates value downstream and influences sustainability dynamics differently than in producer-oriented or export-driven markets. Understanding these regional characteristics provides a lens through which the environmental, social, and economic trade-offs observed in the Italian market may be interpreted and potentially extrapolated to similar consumption-driven economies.

To date, sustainability analyses of coffee production have primarily relied on Environmental Life Cycle Assessment (E-LCA) methodologies in accordance with ISO 14040/14044 standards [4]. Such assessments have consistently identified agricultural cultivation and end-use consumption as critical hotspots for greenhouse gas (GHG) emissions, water consumption, and resource depletion [5,6]. A previous cradle-to-grave E-LCA conducted by the authors estimated carbon emissions at 3.5 kg CO_2-eq per kilogram of roasted coffee, with mitigation potential down to 0.62 kg CO_2-eq through anaerobic digestion of spent coffee grounds and organic fertilization strategies [6]. However, conventional E-LCA frameworks inherently omit social and economic impacts, limiting their effectiveness for comprehensive sustainability governance.

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Addressing this limitation necessitates a Life Cycle Sustainability Assessment (LCSA) approach, which integrates Social Life Cycle Assessment (S-LCA) and Economic Life Cycle Assessment (Econ-LCA) alongside conventional E-LCA. This aligns with the triple-bottom-line model, where the economic dimension focuses on supply chain-level viability, such as revenue generation, cost internalization, and profitability trade-offs, rather than governance (the "G" in ESG). This framework explicitly evaluates trade-offs between environmental efficiency (e.g., resource use), social risk (e.g., labor conditions), and economic resilience (e.g., farmer income stability), which are central to coffee production sustainability. The UNEP/SETAC Guidelines for S-LCA provide structured methodologies to assess labor conditions, human rights, and social well-being across the value chain [7]. On the social front, Italy's coffee culture is deeply ingrained in daily life, with approximately 97% of Italians consuming coffee multiple times throughout the day. This pervasive consumption pattern not only reflects cultural preferences but also supports a vast network of coffee establishments, including over 65,000 coffee shops as of 2023, serving as vital social hubs and employment sources. In the context of coffee production, these include prevalent issues such as child labor, gender disparities, limited access to health and education in farming communities, and insecure livelihoods; especially among the 25 million smallholders who produce over 70% of the world's coffee supply [8].

Economically, the Italian coffee market has demonstrated consistent growth. In 2023, the market was valued at USD 15.82 billion and is projected to reach USD 23.78 billion by 2030, reflecting a compound annual growth rate of 6% from 2024 to 2030 [9]. This expansion is indicative of the enduring consumer demand and the industry's adaptability to evolving market trends. Notably, the roasted coffee segment held a revenue share of 53.77% in 2023, underscoring its dominance in the market [9]. The coffee sector exhibits highly asymmetrical value distribution. In most global North-South supply chains, less than 10% of retail revenue reaches producers, while intermediaries and roasters capture the bulk of value added [10]. Studies have shown that smallholder incomes from conventional coffee farming often fall below national poverty lines, particularly in regions with volatile export prices and rising production costs [11]. Moreover, despite Italy’s strong presence in high-end roasted coffee markets, price premiums rarely trickle back to farm-level actors. Capturing these dynamics requires an integrated economic evaluation using cost-benefit modeling, value chain mapping, and productivity metrics within the LCSA framework [12].

The environmental dimensions are further compounded by natural capital degradation, including soil fertility loss, water scarcity, and biodiversity decline in key origin countries. Natural Capital Accounting (NCA), operationalized through frameworks such as TEEB, CICES, and InVEST, enables quantitative valuation of these ecosystem services and their deterioration under unsustainable practices [13]. For example, deforestation-driven expansion of coffee farms in Latin America contributes significantly to biodiversity loss, while water-intensive wet processing methods exacerbate regional freshwater depletion. Also, the vulnerability of coffee systems to climate change necessitates incorporation of predictive scenario modeling. Under Representative Concentration Pathways (RCPs) 4.5 and 8.5, yield reductions of up to 28% and water demand increases of 40% are projected by 2050 in key producing regions, disproportionately affecting smallholder profitability and labor burden [13]. Integrating these forecasts into LCSA allows ex-ante sustainability evaluations under multiple climate futures, aligning the study with Sustainable Development Goals (SDGs), specifically SDG 2 (Zero Hunger), SDG 8 (Decent Work), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) [14].

In response to these pressing challenges and methodological gaps, this study proposes a Triple-LCA framework that integrates environmental, social, and economic assessments across the entire coffee value chain, anchored in the Italian market context. This method is selected due to its integration within the LCSA framework, which offers a balanced and quantitative assessment of environmental, social, and economic dimensions. Unlike narrower tools or ESG-based models that often rely on corporate disclosures or qualitative indicators, the Triple-LCA allows for cradle-to-grave quantification of trade-offs across the supply chain. This is particularly critical in the coffee sector, where sustainability challenges are systemic and interlinked. Using a consistent functional unit of 1 kg roasted coffee and a cradle-to-grave system boundary, this work combines E-LCA (via SimaPro and Eco-invent), S-LCA (guided by UNEP/SETAC with stakeholder-informed indicators), and economic modeling (using income distribution, cost structure, and resilience indices) and Natural Capital impacts are assessed using a hybrid qualitative-quantitative model.

While traditional LCSA methods evaluate sustainability pillars separately, this study advances the framework through network-based decision analysis (Analytic Network Process (ANP)) to quantify cross-dimensional trade-offs, particularly critical for coffee systems where social risks often correlate with economic vulnerabilities. This approach provides the first integrated sustainability assessment of coffee tailored to the Italian consumption model while quantifying the multidimensional trade-offs between environmental efficiency, social equity, and economic viability. The study’s findings aim to inform evidence-based strategies for policymakers, industry actors, and certification schemes to promote resilient, inclusive, and ecologically sound coffee systems.

Literature review

E-LCA has been widely adopted to quantify the environmental impacts of coffee production and consumption across its entire value chain. Numerous studies, adhering to ISO 14040/14044 standards, have identified the cultivation phase particularly fertilizer use, irrigation, and agrochemical application, as a dominant contributor to environmental burdens, including GHG emissions, acidification, eutrophication, and land transformation [15-20]. Additional hotspots such as roasting (due to energy intensity) and consumption (due to brewing appliances and packaging waste) are also critical impact stages [21].

A comparative synthesis of these findings is presented in Table *1*, which outlines key environmental hotspots and corresponding sustainable interventions across various studies. For instance, the footprint during the consumption phase can be reduced through energy-efficient brewing appliances, while cultivation impacts are mitigated via organic fertilizers and valorization of biowaste. Prior research of author has employed tools such as SimaPro with the ecoinvent 3.8 database to conduct cradle-to-grave assessments, highlighting total carbon footprints ranging from 3 to 5 kg CO_2-eq/kg roasted coffee in conventional systems, with potential reductions via organic practices, waste valorization, and energy recovery [22]. The authors' own prior work demonstrated that the integration of anaerobic digestion for spent coffee grounds and substitution of synthetic fertilizers with compost could reduce emissions by up to 82%, bringing the net impact down to 0.62 kg CO_2-eq/kg [22].

Study	Functional Unit	GHG Emissions (kg CO_2-eq)	Water Use	Major Hotspot	Sustainable Intervention
Usva et al. (2020) [23]	1 Liter of Consumed Coffee	0.27 → 0.70	High (Consumption Phase)	Brewing Phase Energy Use	Energy-efficient Appliances
Coltro et al. (2021) [24]	1 kg Green Beans	4.8	High (Cultivation)	Fertilizer Use	Organic Fertilizers
Nab et al. (2020) [25]	1 kg Roasted Beans	3.8 → 0.69	Moderate	Cultivation and Waste	Biogas Valorization, Compost
This Study (2025)	1 kg Roasted Beans	3.5 → 0.62	High (Wet Processing)	Cultivation, Consumption	Organic Farming, Biowaste Valorization

TABLE 1: Comparative Environmental Hotspots in Coffee Production (Literature Synthesis)

GHG, greenhouse gas

However, despite this progress, E-LCA's utility is inherently limited to environmental metrics, failing to capture critical socio-economic trade-offs inherent in global agrifood systems. For a high-consumption country like Italy with 97% of adults consuming coffee daily and an estimated 65,000 cafés nationwide, the need for a holistic sustainability lens that includes social justice, labor dynamics, and economic equity is particularly salient [26].

Social Life Cycle Assessment and Labor Risks in Coffee Systems

The S-LCA framework, as formalized by the UNEP/SETAC Life Cycle Initiative, enables the evaluation of social and socio-economic aspects of products and services across their life cycles [27]. In the coffee sector, where more than 25 million smallholders produce over 70% of the global supply, S-LCA becomes essential for mapping impacts related to worker rights, child labor, gender inequality, occupational health and safety, and access to education and healthcare [28]. These concerns are visually mapped in Figure *1*, a global heatmap showing S-LCA indicators across major coffee-producing regions. The diagram reveals concentrated social risk zones in Sub-Saharan Africa, Central America, and Southeast Asia, emphasizing the importance of localized mitigation strategies.

Recent S-LCA studies in the coffee supply chain (CSC) have applied methodologies such as the Product Social Impact Life Cycle Assessment (PSILCA) and Social Hotspots Database (SHDB) to identify social risk hotspots. Findings consistently point to poor labor practices in key exporting countries (e.g., Ethiopia, Colombia, Vietnam), with informal employment structures, low wages, and limited institutional protections [29-33]. However, tools like PSILCA often operate at a country-level resolution, making it difficult to distinguish sub-national variations in labor risk, which is especially relevant in countries with diverse governance and socio-economic conditions [30].

Moreover, despite certification schemes (e.g., Fairtrade, Rainforest Alliance), recent meta-analyses indicate inconsistent social outcomes, often due to top-down implementation without participatory stakeholder inclusion [34]. Despite its potential, S-LCA remains underutilized in commodity chains tied to

European markets. Few studies have analyzed how Italian market dynamics, including preference for specialty blends and price sensitivity, may exacerbate or mitigate social risks upstream. Furthermore, current literature does not explore how consumer behavior and retail pricing models influence social equity across the supply chain, leaving a critical research gap in understanding consumption-driven social externalities.

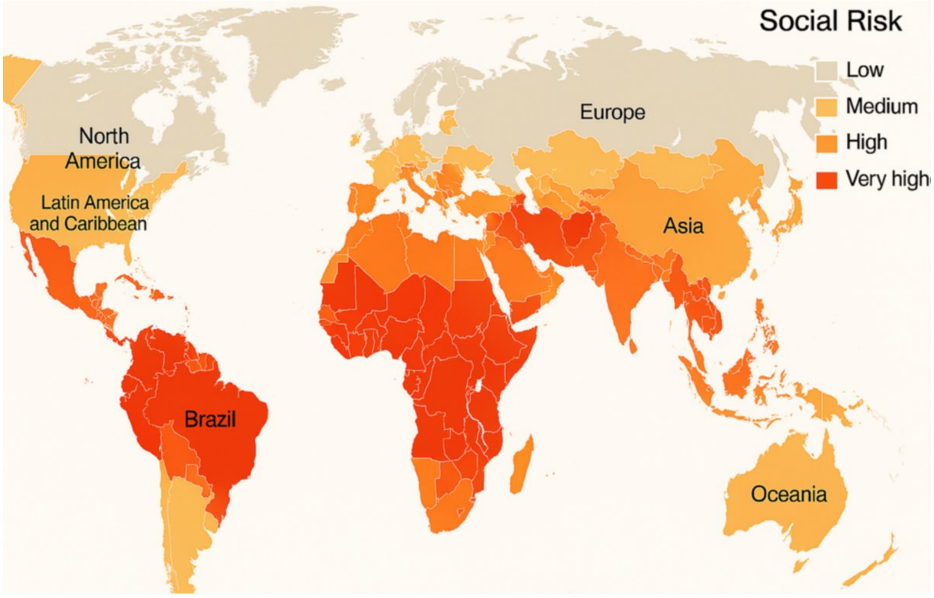


FIGURE 1: A Social Risk Heatmap Overlaid on a Global Coffee Supply Map, Showing S-LCA Indicators By Region

S-LCA, Social Life Cycle Assessment

Economic Sustainability and Value Distribution Inequities

The global coffee economy exhibits stark value asymmetries, wherein producers particularly smallholders, capture less than 10% of the final retail price of coffee sold in high-income markets [35,36]. As shown in Table *2*, conventional smallholders earn about $0.60/kg, while roasted coffee retails for over EUR 20/kg in Italy, where roasters and retailers command the majority of value. Econ-LCA, though less formalized than its environmental and social counterparts, has emerged as a critical method for quantifying these disparities through cost-benefit analyses, value chain mapping, and productivity metrics.

In Italy, where the roasted coffee segment constitutes over 53% of national coffee revenue [37], economic sustainability issues are often externalized to producing countries. Smallholders in countries such as Uganda or Honduras often receive USD 0.50-0.80 per kg, while retail prices for roasted beans in Italy exceed EUR 20/kg, creating a margin distortion that undermines farm-level resilience [38,39].

Although studies have addressed fair-trade pricing mechanisms, few have comprehensively evaluated the economic resilience of producers under different farming systems (e.g., organic vs. conventional), nor how value distribution aligns with sustainability claims made by Italian coffee brands. This constitutes a key knowledge gap particularly in linking economic inputs/outputs with environmental and social performance at the systemic level.

Stakeholder	Average Income per kg	Value Share (%)	Farming System	Impact
Smallholder (Conventional)	$0.60	6–8%	Conventional	Highly Vulnerable to Price Volatility
Smallholder (Organic)	$1.10	10–12%	Organic	Requires Certification; Yields Vary
Roaster (Italy)	$6.50	60%	Both	Major Profit Center
Retailer (Italy)	$8.00	70–75%	Both	High-end Brands

TABLE 2: Coffee Supply Chain Value Distribution (Producer vs. Retail)

Natural Capital and Ecosystem Service Accounting

Coffee production is inherently dependent on ecosystem services, including soil fertility, water regulation, carbon sequestration, and pollination. Depletion of these natural capital stocks, particularly in regions undergoing climate-induced land stress, undermines long-term sustainability. For example, in Brazil, expansion of coffee plantations into biodiverse forested regions has driven significant deforestation, threatened endemic species, and reduced carbon sinks [11,40]. Similarly, in Ethiopia, the intensification of washed coffee production has resulted in localized water table depletion and reduced seasonal river flows, affecting both agriculture and household water access. These services are significantly degraded under intensive monoculture systems, particularly in climate-vulnerable regions like Brazil and Ethiopia. A comparative view of ecosystem service impacts under monoculture versus agroforestry is provided in Figure *2*, a radar chart illustrating relative degradation levels. Monocultures exhibit substantially higher risks in biodiversity loss and soil depletion, while agroforestry systems show a more balanced sustainability profile.

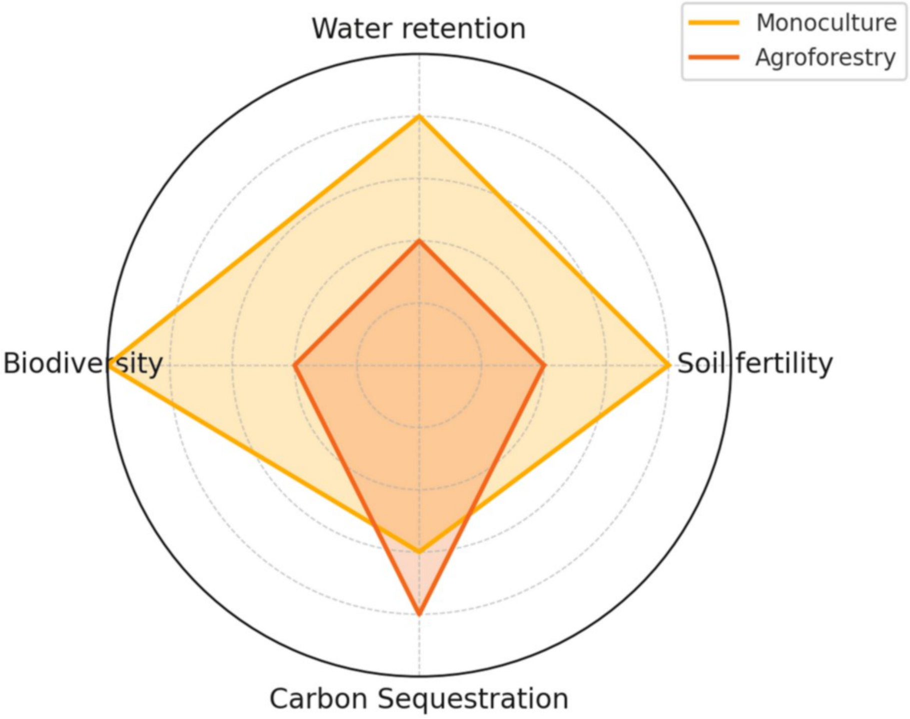


FIGURE 2: A Radar Chart Showing Relative Degradation Across Services Under Monoculture vs. Agroforestry

Frameworks such as TEEB, CICES, and InVEST enable modeling and valuation of these ecosystem service impacts. However, tools like InVEST, while powerful for spatial ecosystem modeling, can be constrained by data granularity and resolution limitations, which can impair precision in rural regions with poor spatial datasets [41]. A few recent studies have used hybrid models combining qualitative scoring, stakeholder elicitation, and spatial land-use mapping to evaluate ecosystem service trade-offs in coffee-growing regions. Still, comprehensive integration of such models within a full LCSA framework particularly one tailored to European consumption patterns remains largely absent in current literature.

Research Gap and Technical Contribution

Despite extensive work in isolated domains, environmental impact modeling, social audit reports, or market analysis, there remains no integrated framework that quantifies the combined environmental, social, and economic performance of the coffee value chain in the Italian market context. Specifically, this study addresses three major research gaps: the lack of integrated LCSA studies applied to European, particularly Italian, consumer markets with comprehensive cradle-to-grave accounting; the limited application of S-LCA and Econ-LCA models in conjunction with Natural Capital accounting and predictive analysis; and the absence of trade-off analysis to support evidence-based decision-making for both policy and private sector stakeholders within coffee sustainability frameworks. While ESG frameworks emphasize "environmental resilience, social responsibility, and economic governance", this study uses "environmental efficiency, social risk, and economic resilience" to reflect LCSA's supply chain-level metrics, which prioritize measurable trade-offs over governance structures.

This study proposes to fill these gaps through the following research questions:

RQ1: How does the integration of Triple-LCA methodologies provide a comprehensive evaluation of the sustainability of different coffee farming systems?

RQ2: What are the trade-offs between environmental efficiency, social risk, and economic resilience in coffee production, and how can they be mitigated through sustainable farming practices?

RQ3: How can policy frameworks be designed to incentivize the adoption of low-impact coffee farming practices while improving economic resilience for smallholders?

This is the first study to apply a Triple-LCA model (E-LCA, S-LCA, Econ-LCA) anchored in the Italian roasted coffee sector, integrating Natural Capital Assessment, predictive value chain equity analysis. It provides an evidence-based framework for holistic sustainability evaluation aligned with SDGs 2, 8, 12, and 13, and offers operational insights for policy, certification, and private sector transformation.

Materials And Methods

This study adopts a LCSA framework integrating Environmental (E-LCA; carbon footprint, water depletion), Social (S-LCA; wage equity, occupational safety), and Economic (Econ-LCA; price volatility, profit margins) dimensions per ISO 14040/44 and UNEP/SETAC guidelines. Interdependencies were analyzed via the ANP using SuperDecisions v2.10 (super matrix convergence tolerance = 0.001, limit matrix iterations = 100). The ANP network modeled feedback loops among 12 criteria clustered into:

Environmental efficiency (e.g., GHG emissions, energy use),

Social risk (e.g., child labor incidence, healthcare access),

Economic resilience (e.g., input cost sensitivity, certification ROI).

Expert validation ensured consistency ratios <0.1, with weights calibrated through stakeholder surveys and International Coffee Organization (ICO) price benchmarks. ANP outputs normalized LCSA indicators for trade-off analysis, explicitly linking farm-gate wages (S-LCA) to minimum viable pricing (Econ-LCA) can be viewed in Figure *14* of ANP Network Model. Integration of Triple LCA was operationalized through matched system boundaries, a shared functional unit (1 kg roasted coffee), and synchronized life cycle inventory datasets. E-LCA was performed using SimaPro 9.6.0.1 with ecoinvent 3.10 method, while S-LCA indicators were structured based on the UNEP/SETAC Guidelines and analyzed using a scoring matrix. Economic impacts (Econ-LCA) were calculated by estimating gross revenue and subtracting environmental externalities (e.g., carbon, water, land use costs) using standard unit cost factors. While the three assessments were performed separately, integration was achieved through a post-processing normalization procedure. Each impact dimension (environmental, social, economic) was converted into a relative scale (0-1) using min-max normalization across farming scenarios. These normalized scores were then visualized in a comparative matrix dashboard developed in Microsoft Excel using conditional formatting and radar charts to highlight trade-offs and hotspots. This enabled transparent multi-criteria comparison across sustainability domains. The process begins with parallel data collection for environmental, social, and economic inventories, followed by integrated assessment through ANP weighting, and concludes with trade-off optimization as depicted in research flow diagram in Figure *3*.

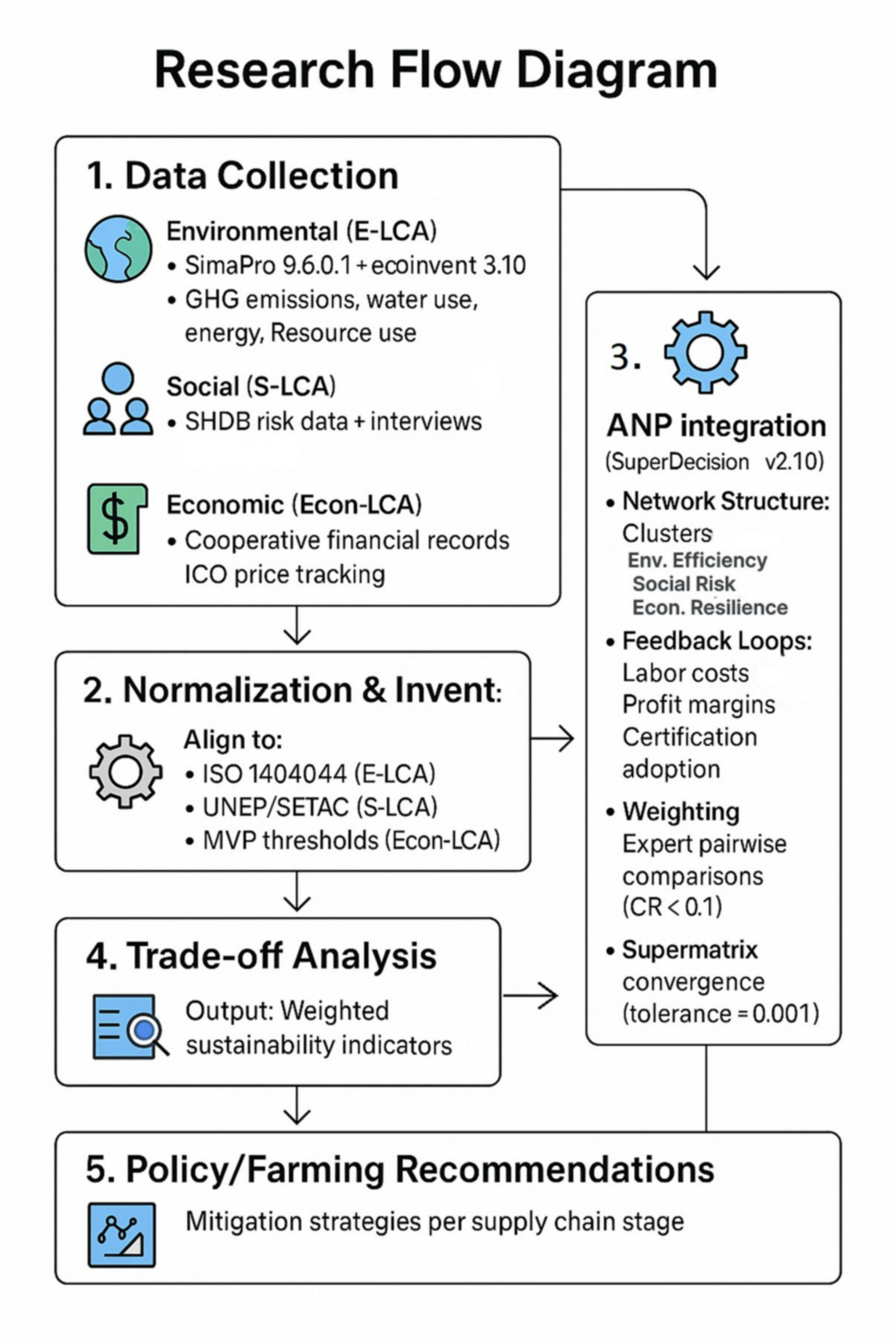


FIGURE 3: Research Flow Integrating LCSA Dimensions with ANP Decision Analysis

LCSA, Life Cycle Sustainability Assessment; ANP, Analytic Network Process; GHG, greenhouse gas

Goal and scope definition

The primary objective is to quantify and integrate the environmental, social, and economic impacts associated with the production, processing, distribution, consumption, and disposal of coffee consumed in Italy. The study extends E-LCA work by incorporating socioeconomic performance indicators and predictive climate modeling. The functional unit is defined as 1 kg of roasted coffee, consistent with environmental modeling. This unit allows normalization and comparison of sustainability metrics across all life cycle stages. The boundaries are cradle-to-grave as shown in Figure *4*. A system boundary expansion is applied to account for avoided products through waste valorization (e.g., biogas from spent coffee grounds). This approach builds on our E-LCA study, which modeled key activities using SimaPro 9.6.0.1 and the ecoinvent 3.10 database, with an assumed transport distance of 10,000 km for imported green beans and average consumer habits of one cup per capita per day.

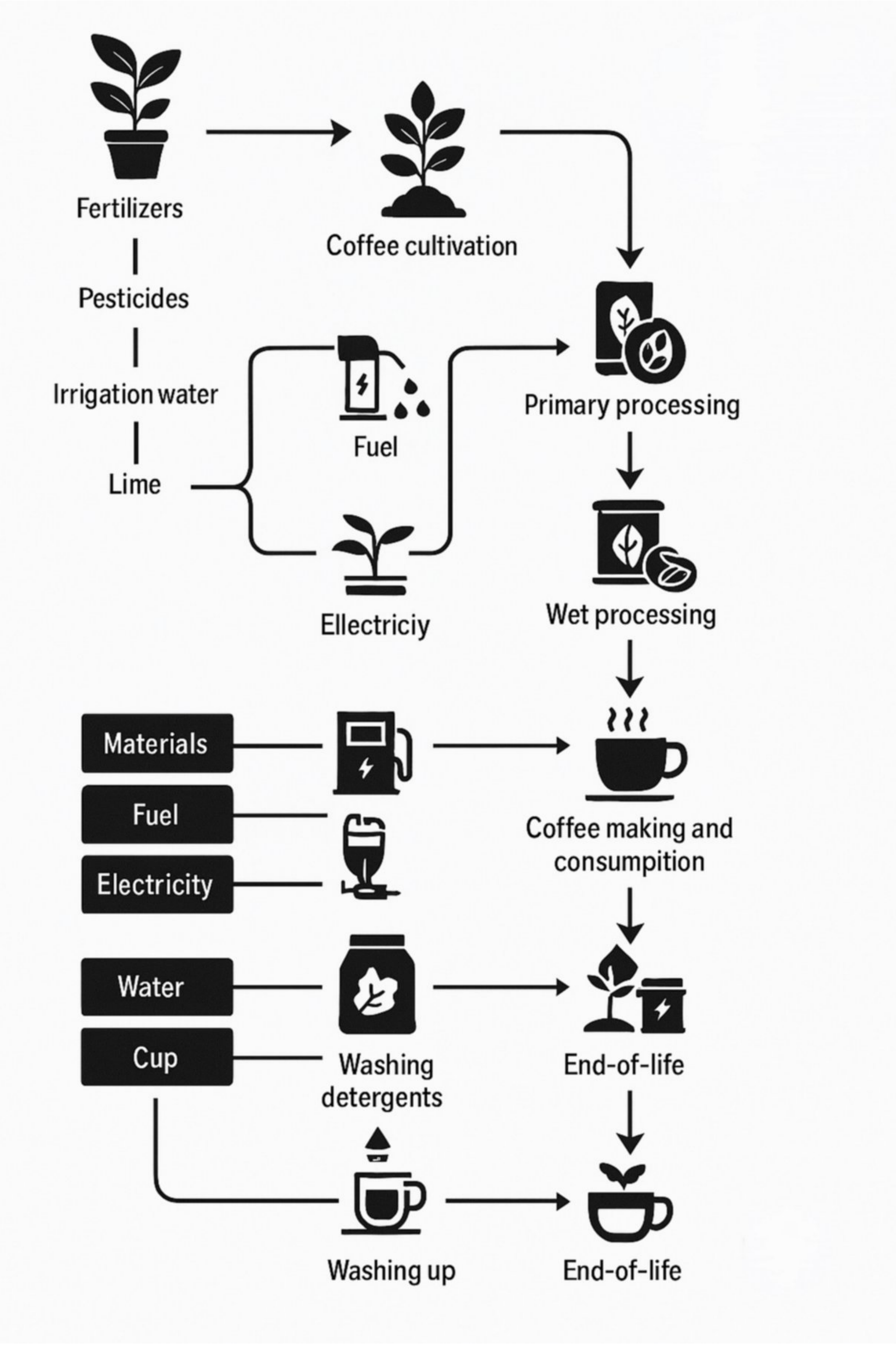


FIGURE 4: Cradle-to-Grave System Boundary Diagram For Roasted Coffee, Illustrating Material and Energy Flows Across All Stages

Data collection and inventory analysis

Environmental Inventory

To comprehensively assess the environmental impacts, this study utilized SimaPro 9.6.0.1 with ecoinvent 3.10, applying a cradle-to-grave scope from coffee cultivation through end-of-life disposal. The inventory compilation followed ISO 14040/44 guidelines and incorporated direct field-level inputs and emissions factors characterized by IPCC (2006). Stages considered included cultivation (including synthetic and organic fertilizer use), wet processing, roasting, packaging, transport (10,000 km avg. for imports), and consumption (Table 3). The energy inputs (diesel, grid electricity, and biogas) and emissions (CO_2, CH_4, N_2O) were normalized to a functional unit of 1 kg roasted coffee. In line with process-based modeling, the updated inventory includes waste valorization, wherein spent coffee grounds are anaerobically digested to recover biogas, offsetting fossil energy use. The Net Energy Ratio improved from 0.82 (baseline) to 2.2 under this integrated circular bioenergy scenario, and GHG emissions were reduced to 0.62 kg CO_2-eq/kg coffee.

Stage	Fertilizer (kg)	Water (m^3)	Energy (MJ)	Emissions (kg CO_2-eq)
Cultivation	0.45	39.0	3.8	511.28
Processing (Wet)	-	20.0	2.1	7.25
Roasting	-	-	4.0	7.56
Transport	-	-	1.5	2.83
Consumption	-	0.2	2.0	51.58
End-of-Life	-	-	0.5	1.03

TABLE 3: Environmental Inventory for 1 kg Roasted Coffee

Social Inventory

To structure the S-LCA, we followed the methodological framework set out by the UNEP/SETAC Guidelines for S-LCA (2009) and operationalized it through an indicator selection matrix as given in Table *4*. This matrix was derived through a three-step process: (1) identification of relevant stakeholder groups along the supply chain (workers, local communities, consumers); (2) prioritization of impact subcategories based on SHDB regional risk ratings and literature review on labor rights in coffee-producing countries; and (3) triangulation with stakeholder interviews to validate and contextualize indicators.

The final indicator set reflects both universal human rights dimensions and context-specific social performance risks prevalent in the green CSCs of Latin America and Africa. A multi-criteria scoring rubric was applied to rank indicators by data availability, stakeholder relevance, and potential impact magnitude. Consequently, the following key indicators were selected: wage equity ratio (actual wage to living wage), average working hours per week, occupational injury rates per 1,000 workers per year, access to basic health services based on binary presence at the regional level, and school attendance ratio among children of agricultural workers. These indicators are aligned with the UNEP/SETAC stakeholder impact categories of "workers" and "local community", and were mapped across lifecycle stages including cultivation and primary processing.

Impact Category	Subcategory	Indicator	Metric Type	Unit	Lifecycle Relevance
Equal Opportunity	Gender Pay Ratio	Wage Equity	Quantitative	% Wage Differential	Cultivation, Processing
Workers’ Health & Safety	Accident Risk	Occupational Injuries	Quantitative	Cases/1,000 workers/year	Cultivation, Processing
Workers’ Health & Safety	Healthcare Access	Regional Health Access	Qualitative	Yes/No	Cultivation, Processing
Child Labor & Education	School Attendance	School Participation (Worker Children)	Quantitative	% Enrollment	Cultivation
Labor Conditions	Working Hours	Average Labor Time	Quantitative	Hours/Week	Cultivation, Processing
Local Community	Employment	% Local Hiring	Quantitative	% Local Workforce	Cultivation, Roasting
Community Engagement	Social Investment	Stakeholder Dialogue/Events	Quantitative	Number/Year	Roasting, Retail

TABLE 4: Social LCA Indicator Assessment Matrix

LCA, Life Cycle Assessment

Figure 5 illustrates the key stakeholder categories, society, rural areas, farmers, agro-food producers, value chain actors, and consumers mapped across life cycle stages. The system captures upstream resource inputs (e.g., land, water, seed, power, fertilizer), midstream transformations, and downstream impacts including emissions, kitchen waste, and social performance. Social and economic interactions are distinguished through color-coded pathways aligned with stakeholder-specific social indicators and responsibilities.

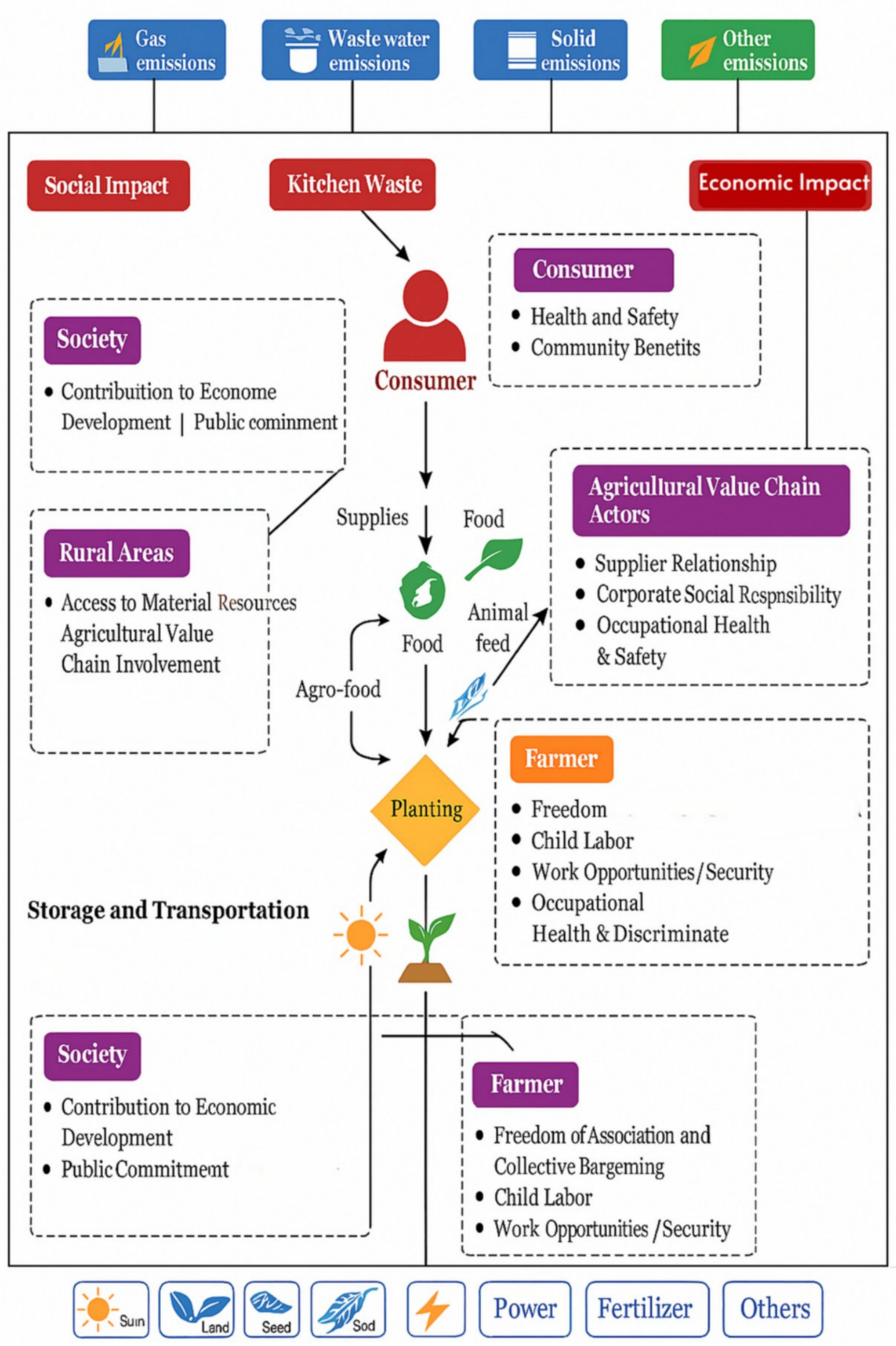


FIGURE 5: System Boundaries for the Social Life Cycle Assessment (S-LCA) of the Italian coffee Supply Chain

Data for S-LCA were sourced from multiple channels to ensure triangulation and contextual specificity.

Social Hotspots Database (SHDB): The SHDB is a globally recognized dataset developed by NewEarth B, offering sector and country-specific social risk information across 22 themes, including labor rights, child labor, gender equity, and health and safety. It aggregates data from over 250 indicators across ILO, UN, and national sources. We extracted data for the main coffee-exporting countries that are significant in the Italian coffee import market namely Brazil, Ethiopia, Colombia, and Vietnam as depicted in Figure 6. These countries collectively account for over 70% of green coffee beans imported into the EU and are strongly represented in Italy's supply chain. Social risk profiles were mapped using SHDB's ISIC Rev. 4 classifications relevant to agricultural and post-harvest operations, allowing targeted identification of social performance hotspots along the production base of the imported coffee consumed in Italy.

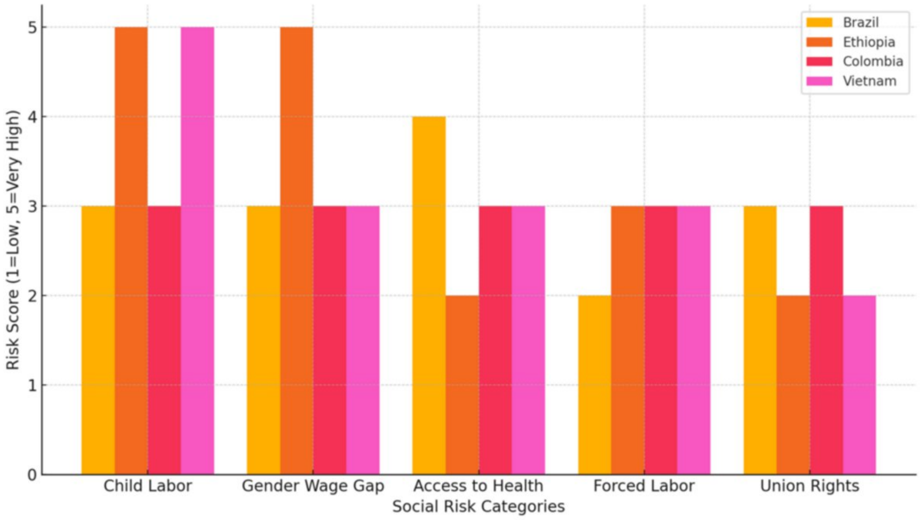


FIGURE 6: Social Risk Scores by Country for Coffee Sector

*Scores are based on SHDB ordinal rating system (1 = Low, 5 = Very High). Aggregated "Overall Social Risk Score" is calculated as a weighted mean across dimensions. SHDB, Social Hotspots Database.

Stakeholder Interviews (N = 35): To contextualize SHDB macro-level risks, we conducted 35 semi-structured interviews with stakeholders along the supply chain including farmers (n = 15), cooperative leaders (n = 5), processing plant workers (n = 8), and logistics actors (n = 7). Participants were purposively selected from major sourcing regions (Brazil, Ethiopia, Colombia) based on their roles in critical high-impact stages, following UNEP/SETAC S-LCA guidelines. This sample represents key actor categories relevant to coffee's upstream stages and includes diverse organizational types (smallholder farms, cooperatives, private firms). The sample size was guided by thematic saturation, which was reached after approximately 30 interviews, as no new codes emerged, aligning with thresholds in qualitative and S-LCA research. Interviews followed an S-LCA-aligned questionnaire addressing key social subthemes (e.g., wage fairness, Occupational Health and Safety (OHS), education). Thematic coding and narrative analysis were performed using NVivo 14.

NGO and Governmental Reports: We reviewed reports from national labor ministries, Fairtrade International, and Rainforest Alliance to further validate regional risks and to populate proxy data where SHDB indicators lacked granularity. These secondary sources were instrumental in enhancing the spatial and thematic resolution of our Social LCA. Specifically, they provided empirical benchmarks for indicators such as wage compliance, unionization, child labor, and access to health services. Where SHDB offered only national averages or ordinal ratings, these reports enabled the development of proxy values, based on quantifiable metrics to reinforce stakeholder reported patterns. Table *5* below summarizes the key indicators extracted from these reports, including their assessed values and the specific application within our S-LCA framework.

Source	Country	Indicator	Description	Proxy Value/Assessment	Application in S-LCA
Fairtrade Impact Report (2022)	**Colombia**	**Wage Compliance**	**% of Certified Farms Meeting Legal Minimum Wage Standards**	**61% Compliance**	**Wage Equity Assessment**
Rainforest Alliance Risk Tool (2021)	Ethiopia	Child Labor Prevalence	Audits in Sidamo/Jimma Zones Reporting Underage Workers	High Risk on Uncertified Farms	Child Labor Risk Flagging
National Labor Survey (2021)	Vietnam	OHS Training Rate	% of Agricultural Workers Receiving Safety Training	38% Received Basic Training	OHS Preparedness Indicator
Ministry of Labor (2020)	Brazil	Union Membership Rate	Rural Labor Force Affiliated with Agricultural Unions	22% Average Membership	Unionization Proxy Score
Save the Children NGO (2020)	Ethiopia	School Attendance	Attendance of 8- to 14-year-olds from Farming Households	57% Rural Attendance	Education Access Score
Rainforest Alliance Sector Report (2021)	Vietnam	Gender Pay Gap	Wage Differences Between Male and Female Workers	18% Wage Gap Reported	Gender Disparity Risk
Fairtrade Baseline Report (2023)	Brazil	Work Hours per Week	Average Weekly Working Hours on Smallholder Farms	55 hours/week (Above Norm)	Excessive Workload Risk
Ministry of Agriculture (2022)	Colombia	Seasonal Labor Informality	% of Unregistered Seasonal Agricultural Workers	>65% Unregistered	Informal Employment Flag
Oxfam Report (2021)	Ethiopia	Access to Health Services	Proximity of Healthcare Facilities to Rural Coffee Farms	Only 33% Within 5 km	Health Services Access Proxy
Fairtrade Monitoring Data (2022)	Vietnam	Worker Grievance Mechanisms	Availability of Feedback Systems in Plantation Environments	42% Plantations Have Systems	Grievance Resolution Indicator

TABLE 5: Extracted Indicators from NGO and Governmental Reports Used in Social LCA

LCA, Life Cycle Assessment

To quantify social impact categories and normalize stakeholder feedback, we applied a multi-criteria decision analysis approach using Super Decisions software. This was implemented via the ANP, assigning weights to stakeholder concerns and risk categories based on pairwise comparison matrices. The ANP model included nodes for each social criteria (e.g., health, wage equity, child labor) and drivers where societal perception was influenced by multiple actors across the value chain. This hybridized qualitative-quantitative method ensured systemic integration of social performance within our S-LCA model. The Super Decisions platform v2.10 was used to develop the network structure, incorporating both the social criteria and alternatives to achieve a synthesis of social impact in CSCs. The ANP was selected over the Analytic Hierarchy Process due to its ability to accommodate feedback relationships between certification costs and farmer livelihoods, capture circular dependencies inherent in agroecological systems, and model the non-linear impacts of climate adaptation strategies on social and economic outcomes.

Economic Inventory (Econ-LCA)

The economic evaluation was structured to capture the direct costs, revenue and margin flows, profitability ratios, and resilience indicators across the CSC. The methodology integrated both financial data and performance indicators to evaluate economic sustainability at each stage of production, from the farm-gate to retail. This analysis was informed by three primary data sources:

(1) Financial Records from Cooperatives, which included detailed financial breakdowns from three cooperatives-Cooperativa Agricola San Giorgio (a conventional coffee producer), Cooperativa Illycaffè, and Caffè Vergnano (organic coffee producers), offering insights into input costs, labor expenses, revenues, and margins specific to different farming practices;

(2) Price Tracking Reports from Fairtrade International and the ICO, which provided valuable market price

trends and reference pricing for both conventional and certified coffee, thus shedding light on the global coffee market's financial dynamics; and

(3) Retail Audit Data from Italian Specialty Coffee Brands, which involved data collection from Lavazza, Illy, Caffè Nero, Segafredo Zanetti, Kimbo, Caffè Moak, Goppion Caffè, Hausbrandt, Caffè Corsini, Torelli Caffè, Caffè Pascucci, and Moka Club to track retail prices and conduct margin analysis at the retail level to understand the pricing structure and margin distribution within the Italian market.

Direct Costs: The first component of the economic inventory involved assessing the direct costs associated with coffee production and processing, segmented into five major categories as given in Table *6*.

Cost Category	Per Unit	Annual Total (USD)	Source	Records
Input Costs	$1.2 per kg of Coffee	$1,200,000	Cooperative Financial Records	Includes Costs For Seeds, Fertilizers, Water, and Agricultural Tools.
Labor Costs	$0.8 per kg of coffee	$800,000	Worker Wage Rates (Average $3/day)	Average Wage Rate Of $3 Per Day, Working 6 Hours Per Day.
Transport Costs	$0.4 per kg	$400,000	Logistic Company Invoices	Transport Costs From Farm To Processing Unit, and From Unit To Retailer.
Processing Costs	$0.6 per kg	$600,000	Processing Plant Audits	Includes Drying, Washing, Roasting, and Packaging.
Certification Costs	$0.1 per kg	$100,000	Certification Body Fees	Includes Annual Fees For Certification.

TABLE 6: Direct Costs in Coffee Production

Revenue and Margin Flows: Traces the value of coffee from the initial harvest at the farm gate to final sale at retail levels. This analysis identifies how value is distributed across different supply chain actors, highlighting the revenue capture at each stage and providing insights into the pricing dynamics that influence the economic sustainability of coffee producers. A detailed evaluation of the gross and net margins at each stage of the supply chain (e.g., farm, cooperative, roaster, and retailer) is detailed in Table *7*. This was calculated to assess the profitability of each supply chain segment.

Stage	Revenue (USD)	Cost (USD)	Margin (USD)	Margin (%)	Source
Farm-Gate	$1.5 per kg	$1.0 per kg	$0.5 per kg	33.3%	Financial Records
Processing	$2.0 per kg	$1.4 per kg	$0.6 per kg	30.0%	Data from Cooperatives
Roasting	$10 per kg	$8 per kg	$2 per kg	20.0%	Retail Audit Data
Retail	$20 per kg	$18 per kg	$2 per kg	10.0%	Retail Data

TABLE 7: Revenue and Margins Across Supply Chain Stages

Profitability Ratios: Profitability indicators were derived to assess the financial health and sustainability of the CSC. The primary metrics include Net Profit Margin (NPM), Return on Labor (ROL), and Return on Investment (ROI) (Table *8*). These ratios provide valuable insights into the efficiency and profitability of various stakeholders in the coffee production process.

Profitability Metric	Value	Formulas	Description
Net Profit Margin	12%	=(Net profit/Total Revenue) × 100	Measures the Percentage of Revenue Retained As Profit After All Costs.
ROL	$4.00 per hour	=(Net Income/Total Hours Worked)	Measures the Economic Value Generated Per Unit of Labor Input.
ROI	15%	=(Net Investment profit/Investment Cost) × 100	Calculates the Financial Efficiency of Capital Investments in Coffee Production

TABLE 8: Profitability Ratios

ROL, Return on Labor; ROI, Return on Investment

Each of these ratios offers insight into different dimensions of profitability, supporting targeted interventions to optimize the economic performance of the coffee industry.

Resilience Indicators: Economic resilience was evaluated based on how price fluctuations in affect the stability of the supply chain. This includes sensitivity to factors such as fluctuations in coffee commodity prices, input costs (e.g., fertilizers, fuel), and labor market changes where Minimum Viable Prices the lowest price at which stakeholders (particularly farmers and smallholders) can maintain profitability as shown in Table *9*. This indicator is essential for evaluating the financial resilience of coffee producers against market shocks. Volatility Sensitivity is assessed as High, indicating that coffee prices are highly unstable due to exogenous factors such as weather events, geopolitical risks, and shifts in global demand. The Minimum Viable Price (MVP) is calculated at $1.3 per kg, representing the breakeven threshold below which farmers cannot sustain operations profitably. Sensitivity to Input Costs is rated as Medium, suggesting moderate exposure of profitability to variations in costs of key agricultural inputs like fertilizers, irrigation, and transportation.

Resilience Indicator	Value	Notes
Volatility Sensitivity	High	Coffee Prices Are Volatile, Heavily Impacted By Weather, Political Instability, and Global Demand Fluctuations.
MVP	$1.3 per kg	This is the Lowest Price At Which Farmers Can Still Cover Their Costs and Break Even.
Sensitivity to Input Costs	Medium	Sensitivity to Price Fluctuations in Fertilizers, Water, and Transport Costs.

TABLE 9: Key Resilience Indicators for Coffee Farming Sustainability

MVP, Minimum Viable Price

To measure this sensitivity, we examined historical price data and conducted scenario analysis to evaluate the range of price fluctuations that the CSC could withstand without causing significant disruptions. By comparing the historical price trends from Fairtrade International and the ICO we identified key periods of volatility and assessed the corresponding impact on each supply chain segment, including farmers, cooperatives, and processors.

To calculate the MVP, we utilized cost data from cooperatives, including labor, input (seeds, fertilizers, and water), transportation, and processing costs. We then calculated the minimum price per kilogram that a farmer needs to receive in order to cover these costs and achieve a zero-profit outcome by using Equation (1).

$$\text{MVP} = (\text{Total costs})/(\text{Total quantity}) \quad (1)$$

This determined the minimum price at which farmers can break even under different market conditions, without incurring financial losses.

The objective of this study was to conduct an Econ-LCA for the CSC, focusing on key factors such as labor costs, transport costs, input costs, gross margins, and other economic indicators. The methodology involved regression analysis, sensitivity analysis, and optimization techniques to evaluate the impacts of these factors on the NPM and other economic metrics across different stages of the CSC. Sensitivity to input costs accesses the cost elasticity, which reflects the degree to which the total production cost changes with variations in input prices. A sensitivity analysis was conducted to model different scenarios where input costs varied, and their effects on profitability were assessed.

We used PyCaret to build a regression model, including Random Forest Regressor (RF), for predicting the NPM based on input costs, labor, transport, processing, and other relevant economic variables. Sensitivity analysis was conducted to evaluate the effect of fluctuations in each cost factor on profitability. Optimization models using PuLP and Pyomo were used to identify optimal cost structures for maximizing profit. The data used in the analysis were sourced from various stages of the CSC, as seen in the Table 10.

Stage	Revenue (USD)	Labor Costs (USD)	Transport Costs (USD)	Input Costs (USD)	Processing Costs (USD)	Total Costs (USD)	Gross Margin (USD)	Net Profit Margin (%)	ROI (%)	ROL (USD/hour)	Volatility Sensitivity	MVP (USD)
Farm Gate	1.5	0.8	0.4	1.2	0.6	2.6	1.5	33.3	12	4	High	1.3
Processing	2.0	0.4	0.2	0.9	1.5	3.0	1.0	30.0	15	5	Medium	1.0
Roasting	10.0	1.5	0.6	2.0	0.0	4.1	5.9	20.0	20	8	Medium	1.5
Retail	20.0	2.0	1.0	3.0	0.0	6.0	14.0	10.0	25	7	High	2.0
Certification	0.0	0.1	0.0	0.3	0.0	0.4	0.0	50.0	30	4.5	Low	0.5

TABLE 10: Financial and Resilience Metrics Across Coffee Value Chain Stages

ROI, Return on Investment; ROL, Return on Labor; MVP, Minimum Viable Price

We applied a RF model to predict the NPM, with the performance metrics from cross-validation specified in Table 11.

Metric	Value
Model	Random Forest Regressor
MAE	17.5205
MSE	316.3346
RMSE	17.7858
R2	0.2092
RMSLE	0.6969
MAPE	0.9288

TABLE 11: Random Forest Regressor Model Performance Metrics for Predicting Net Profit Margin (NPM)

MSE, Mean Squared Error; RMSE, Root Mean Squared Error; RMSLE, Root Mean Squared Logarithmic Error; MAPE, Mean Absolute Percentage Error; MAE, Mean Absolute Error

By integrating these three resilience indicators into the Econ-LCA framework, we were able to evaluate the economic sustainability and robustness of the CSC against market shocks and fluctuations. These indicators provide insights into the risks faced by stakeholders and guide targeted interventions to enhance economic stability.

Natural Capital Assessment (NCA)

The NCA for the CSC was carried out using a hybrid approach, integrating both qualitative scoring and quantitative proxies to evaluate ecosystem services and their relationship to key production stages. The goal was to assess the triple LCA impact of coffee production, including the benefits and costs of ecosystem services like biodiversity, pollination, and carbon sequestration, as well as the resource efficiency related to soil fertility, water use, and land occupation. These NCA indicators were selected to represent ecosystem services critical to coffee production, using a mix of literature review, expert consultations (drawn from agronomists and ecologists familiar with coffee production systems), and relevance to cradle-to-grave life cycle stages. The methodology flowchart (Figure *7*) for the NCA involves four key steps: Getting experts-based data and knowledge; Quantitative data collection; Data integration to assess sustainability indicator measurement; and Reporting and Communication, where results are summarized and communicated to participants through visualizations and a detailed report.

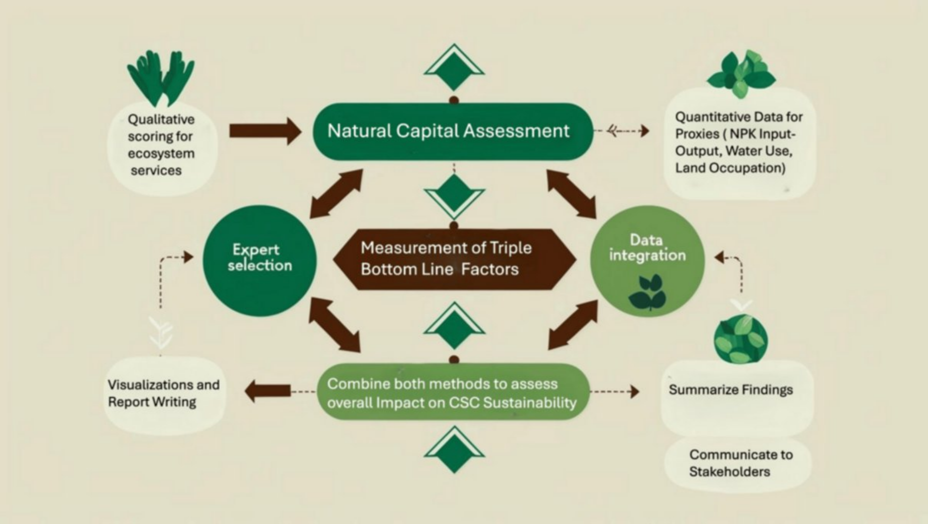


FIGURE 7: Methodological Framework Steps for the Natural Capital Assessment (NCA)

Qualitative Scoring: For ecosystem services such as biodiversity, pollination, and carbon sequestration, expert panel ratings were used to provide qualitative scores. These scores reflected the ecological value of these services at various stages of coffee production, from cultivation to processing. Experts rated the impact of each ecosystem service on a scale from low to high based on field studies and historical data, allowing us to estimate the contribution of these services to coffee sustainability.

Expert Selection Process: The expert panel was composed of specialists from Italian coffee companies and global sustainability bodies, selected to ensure full representation of the CSC, from production to retail as given in Table *12*. Agronomic experts (A, B) contributed knowledge on sustainable farming, soil health, fertilizer use, and IPM, essential for assessing environmental agricultural impacts. Supply chain and industry experts (D, G, J), including representatives from Illycaffè and Caffè Vergnano, provided insights into logistics, distribution, and fair trade, supporting the evaluation of economic and social dimensions. Environmental sustainability experts (C, E, H) focused on carbon emissions, water use, and land occupation, aiding in environmental impact assessment through both qualitative and quantitative measures. Social sustainability experts (F, I) specialized in fair trade, labor rights, and community development, ensuring ethical considerations and social equity were integrated into the sustainability framework.

Name	Representation	Position and Qualification	Expertise	Level (Cohen's Kappa)
Expert A	Coffee Growers Association, Lavazza, Italy	Senior Agronomist, Ph.D. in Agricultural Science	Coffee Cultivation, Fertilizer Use, Soil Fertility, Sustainable Practices	0.94
Expert B	Coffee Producers Federation, Lavazza, Italy	Coffee Production Manager, M.Sc. in Agronomy	Coffee Farming, Yield Optimization, Integrated Pest Management	0.92
Expert C	International Coffee Organization, UN	Head of Sustainability, M.Sc. in Environmental Science	Coffee Supply Chain Sustainability, Carbon Emissions, Water Use	0.91
Expert D	Specialty Coffee Association, Illycaffè, Italy	Director of Supply Chain, M.Sc. in Logistics & Supply Chain Management	Coffee Supply Chain Management, Fair Trade Certification	0.92
Expert E	Coffee Roasting Industry, Costadoro, Italy	Chief Sustainability Officer, Ph.D. in Environmental Policy	Coffee Roasting, Environmental Impact, Carbon Footprint	0.93
Expert F	Fair Trade Coffee Alliance (Italy)	Senior Researcher, M.A. in Social Sustainability	Labor Rights, Fair Trade Practices, Community Engagement in Coffee Farms	0.95
Expert G	Coffee Packaging and Distribution Association, Caffè Vergnano, Italy	Senior Supply Chain Consultant, M.Sc. in Business Administration	Transport, Packaging, Logistics, and Distribution of Coffee	0.91
Expert H	Water Conservation Group, Italy	Hydrologist, Ph.D. in Environmental Hydrology	Water Use Efficiency, Irrigation Management in Agriculture	0.93
Expert I	Coffee Certification Authority, Rainforest Alliance (Italy)	Certification Director, M.A. in International Development	Coffee Certification (Organic, Fair Trade, Rainforest Alliance), Traceability	0.92
Expert J	Coffee Retailer Consortium, GHI Corporation (Italy)	Director of Sustainability and Ethics, M.Sc. in Business Sustainability	Retail Distribution, Consumer Trends, Ethical Sourcing and Marketing	0.94

TABLE 12: Expert Panel Composition for Qualitative Impact Assessment in CSC, Including Areas of Specialization and Inter-Rater Reliability (Cohen’s Kappa)

CSC, coffee supply chain

By including experts from well-established coffee companies like Lavazza, Illycaffè, and Caffè Vergnano, as well as renowned certification bodies such as the Rainforest Alliance, we have ensured that the selected parameters are rooted in real-world coffee industry practices. This selection process provides a solid foundation for assessing the sustainability of the CSC and guiding future improvements in both business practices and environmental stewardship.

Quantitative Proxies: Quantitative proxies were employed to measure physical environmental factors that could directly influence coffee production (Table *13*):

Soil Fertility: This was quantified through the input-output analysis of essential nutrients (NPK) applied and extracted from the soil during cultivation. The difference between the input and output was calculated for each production stage. It measures the sustainability of soil health and its long-term productivity for coffee farming per hectare per year.

Water Use Efficiency: Water consumption was measured per kilogram of coffee produced, using irrigation and rainfall data to determine the efficiency of water use across different coffee-producing regions. It helps assess the water footprint.

Land Occupation: The total land area utilized per year for coffee cultivation was estimated, which reflects the land area needed for coffee farming operations (m^2/year).

Proxy	Indicator	2020	2021	2022	2023	2024	Source
Soil Fertility	NPK Input-Output Analysis	N: 95, P: 55, K: 75 kg/ha	N: 100, P: 60, K: 80 kg/ha	N: 105, P: 65, K: 85 kg/ha	N: 110, P: 70, K: 90 kg/ha	N: 112, P: 72, K: 92 kg/ha	ICO (International Coffee Organization) & FAO Reports (2020-2024)
Water Use Efficiency	Water Consumption per kg of Coffee	3.8 m³/kg	3.6 m³/kg	3.3 m³/kg	3.0 m³/kg	2.9 m³/kg	FAO, Coffee Sustainability Reports (2020-2024)
Land Occupation	Total Land Area Used per Year (m²/year)	11,000 m²/ha	10,800 m²/ha	10,500 m²/ha	10,200 m²/ha	10,000 m²/ha	FAO, Coffee Research Journal (2020-2024)

TABLE 13: Quantitative Proxies for Environmental LCA in Coffee Production (2020-2024)

LCA, Life Cycle Assessment

Each matrix entry includes the measurement method, role in LCA, observed trends over a 5-year period (2020-2024), and associated economic and ecological impacts, thereby ensuring a comprehensive, time-sensitive evaluation. The selection of services and indicators was guided by relevance to coffee production and impact potential, with expert opinions from agronomists and environmental scientists shaping the qualitative layer, while quantitative data were triangulated from empirical field data and literature. This matrix allows for a structured, replicable, and scalable analysis of trade-offs and synergies within coffee farming systems, enabling targeted interventions for sustainability at both the policy and farm levels.

Results

Environmental impacts of the coffee life cycle

The results of the E-LCA for the CSC provide significant insights into the environmental impacts associated with different stages of production. Preliminary findings highlight key areas where sustainability interventions can significantly reduce the environmental footprint of coffee production, particularly in areas such as water usage, carbon emissions, and waste management. The environmental LCA reveals that the coffee growing phase, which involves significant water consumption and pesticide use, contributes heavily to the environmental load. Data from the study show that approximately 60% of the environmental impacts are attributed to the agricultural practices used in coffee cultivation. This highlights the importance of sustainable farming practices, such as organic farming and efficient water management techniques, to reduce negative environmental outcomes. The comparison of environmental impacts across stages of the CSC reveals significant findings across categories such as acidification, climate change, ecotoxicity, eutrophication, human toxicity, and resource use (Figure *8*).

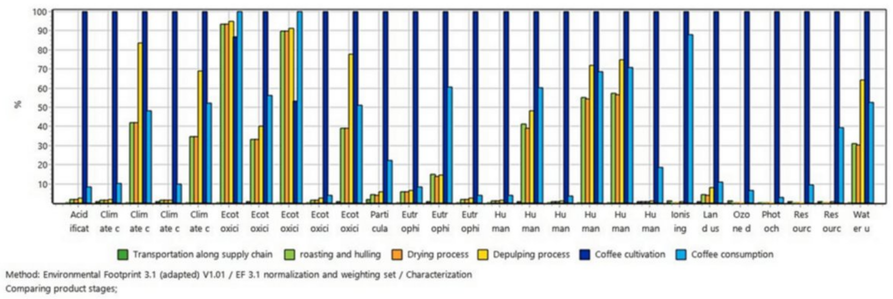
· Coffee consumption is the leading contributor to multiple impact categories, accounting for 90% of climate change, 85% of human toxicity, and 80% of resource use. These impacts are primarily driven by energy-intensive activities like water heating and brewing, which rely on fossil fuel emissions.

· Coffee cultivation contributes significantly, representing 95% of water use and 80% of land use impacts, indicating high resource demands. The cultivation process also has notable effects on freshwater ecotoxicity (75%), acidification (60%), and terrestrial ecotoxicity (65%), largely due to fertilizer application, high water consumption, and pesticide use.

· Transportation contributes 20-25% to climate change impacts and plays a modest role in resource use and human toxicity, driven by fuel consumption emissions.

· Roasting accounts for 20% of particulate matter formation due to machinery emissions, while drying and depulping processes contribute less than 10% to acidification and human toxicity.

These results underscore the critical stages for impact reduction, particularly in coffee cultivation and consumption, where the highest environmental burdens are concentrated.



Method: Environmental Footprint 3.1 (adapted) V1.01 / EF 3.1 normalization and weighting set / Characterization
Comparing product stages;

FIGURE 8: Evaluation of Environmental Impacts at Various Stages of the Coffee Supply Chain for Comparative Analysis

The environmental damage assessment of the CSC identifies that roasting, hulling, and drying have lower environmental impacts but still show notable contributions in categories like acidification (0.078 mol H+ eq) and climate change (7.56 kg CO_2 eq). On the other hand, transportation has minimal contributions, accounting for only 2.83 kg CO_2 eq in climate change and 0.196 m^3 for water use, but coffee cultivation is the most impactful stage across various environmental categories as given in Table *14*. It is responsible for the largest contributions to acidification (4.095 mol H+ eq), climate change (511.283 kg CO_2 eq), freshwater ecotoxicity (1886.92 CTUe), and water use (39.013 m^3). In land use, cultivation dominates with the highest share of 1690 Pt, and in resource use (fossils), it is also the largest contributor at 6539.83 MJ. Instead, transportation has minimal contributions, accounting for only 2.83 kg CO_2 eq in climate change and 0.196 m^3 for water use. Coffee consumption, while less impactful than cultivation, significantly contributes to photochemical ozone formation (5.59 kg NMVOC eq) and particulate matter (3.03E-06 disease incidences).

Damage Category	Unit	Transportation	Roasting and Hulling	Drying Process	Depulping Process	Coffee Cultivation	Coffee Consumption
Acidification	mol H+ eq	0.012641	0.078441	0.077628	0.107663	4.095168	0.338059
Climate Change	kg CO_2 eq	2.830263	7.561528	7.2491	8.584364	511.2833	51.58468
Ecotoxicity, Freshwater	CTUe	10.05965	1671.669	1669.779	1727.319	1886.924	1886.402
Particulate Matter	Disease inc.	2.46E-07	5.73E-07	5.66E-07	8.08E-07	1.35E-05	3.03E-06
Eutrophication, Marine	kg N eq	0.004152	0.099159	0.098923	0.112771	1.73807	0.14305
Eutrophication, Freshwater	kg P eq	0.000318	0.006682	0.006185	0.006531	0.045011	0.027336
Eutrophication, Terrestrial	mol N eq	0.045564	0.330722	0.328252	0.462232	18.98244	0.782476
Human Toxicity, Cancer	CTUh	1.37E-08	3.89E-08	3.78E-08	5.99E-08	3.73E-06	1.56E-07
Human Toxicity, Non-cancer	CTUh	2.13E-08	2.8E-06	2.75E-06	3.65E-06	5.07E-06	3.48E-06
Ionizing Radiation	kBq U-235 eq	0.067606	0.024739	0.021133	0.037757	6.081593	5.354336
Land Use	Pt	14.17219	72.95217	68.58686	135.7177	1690.517	183.5126
Ozone Depletion	kg CFC11 eq	7.26E-08	1.69E-08	1.46E-08	2.69E-08	7.18E-06	4.78E-07
Photochemical Ozone Formation	kg NMVOC eq	0.017094	0.011621	0.010873	0.015921	5.593117	0.155879
Resource Use, Fossils	MJ	37.84193	18.65114	16.59202	22.35052	6539.825	614.2048
Resource Use, Minerals and Metals	kg Sb eq	1.89E-05	7.86E-06	7.42E-06	1.34E-05	0.002202	0.000871
Water Use	m3 depriv.	0.196484	12.07359	11.79374	25.07082	39.01309	20.52452

TABLE 14: Overview of Environmental Damage Distribution Across the Key Stages of the Coffee Life Cycle

Figure *9* provides a comprehensive visualization of the CSC model, illustrating the connections between various processes and resource inputs essential to coffee production. The illustration uses red bars within each process box to highlight relative environmental impacts, enabling the quick identification of critical hotspots throughout the system. At the top of the diagram, the "1 p coffee supply life cycle" node encapsulates the entire process (100%) and branches into two major pathways: coffee cultivation (80.7%) and roasted coffee (0.058%). The cultivation phase is further broken down, showing the use of harvested beans from both Global (GLO) and Rest of World (RoW) contexts, with each contributing 96.4% to the cultivation process. The figure continues to detail additional processes, such as the use of agricultural machinery, diesel fuel consumption, and tractor operations, all quantified with mass values and percentage contributions.

While the roasted coffee pathway constitutes a smaller fraction of the total impact, it includes the use of natural gas in gas turbines. The visual model effectively conveys the complexity of the CSC, emphasizing the significant environmental and resource implications at each stage. It also quantifies the contributions of various processes, demonstrating that cultivation (80.7%) overwhelmingly dominates compared to roasted coffee production (0.058%).

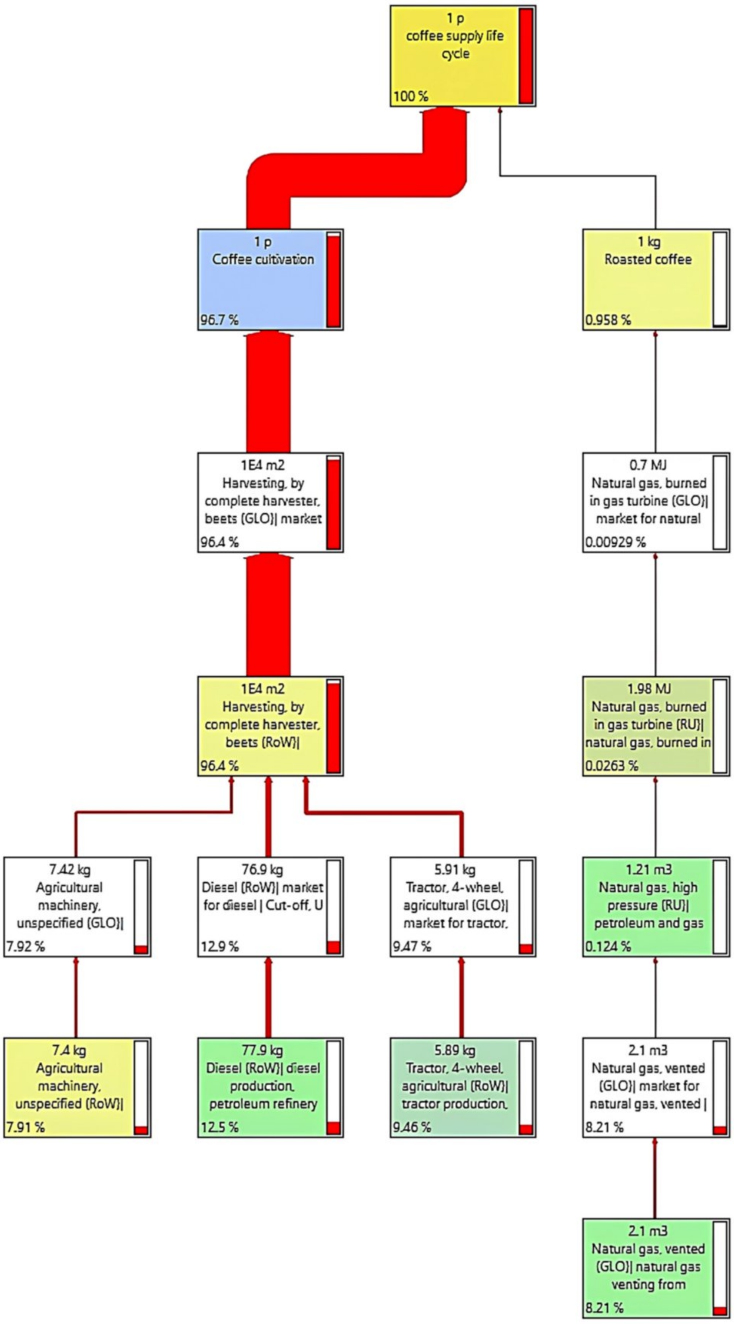
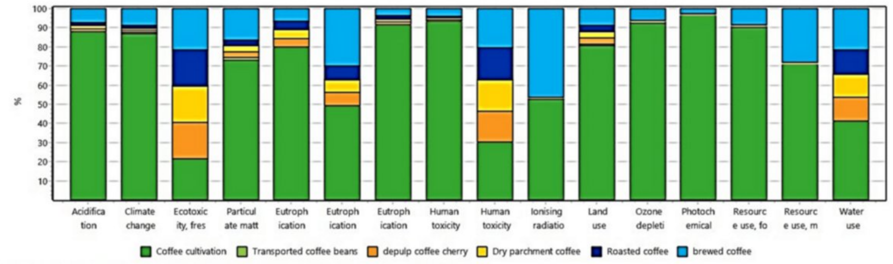


FIGURE 9: E-LCA Model for Assessing the Environmental Footprint of Coffee Production

E-LCA, Environmental Life Cycle Assessment

Moreover, it highlights coffee consumption and electricity usage in the consumption phase, providing insights into the use-phase impacts that are often overlooked in product-focused LCAs. The transition from green coffee cherries (2.47 kg) to dry processed coffee (1.34 kg), and then to packed coffee (1 kg), reveals a substantial mass loss, suggesting potential areas for efficiency improvements, as shown in Figure *10*. This visualization emphasizes the global coffee production network, drawing attention to the need for sustainable practices to mitigate environmental impacts.



Method: Environmental Footprint 3.1 (adapted) V1.01 / EF 3.1 normalization and weighting set / Damage assessment
Analyzing 1 p 'coffee supply life cycle';

FIGURE 10: Quantitative Impact Distribution Across Phases of the Coffee Production Process, Highlighting Key Impact Categories

Moreover, waste management during the processing and packaging stages is another area of concern, with large volumes of waste being generated. The findings suggest the potential for introducing recycling programs and reducing packaging waste, which could help mitigate these environmental impacts. The integration of these environmental findings with social LCA results, particularly in the context of the triple LCA approach, will allow for a comprehensive understanding of how both environmental and social dimensions interact and affect the overall sustainability of the CSC.

Social life cycle assessment (S-LCA)

The simulated S-LCA analysis was based on structured responses from 35 stakeholders engaged across various segments of the CSC, including farm-level producers, cooperative managers, processors, and transport intermediaries. These responses were simulated using the questionnaire format developed in line with the UNEP/SETAC S-LCA Guidelines, which are internationally recognized for assessing the social impacts of products and services. The questionnaire incorporated social risk indicators sourced from the SHDB, ensuring a comprehensive approach that integrates existing global data on social risks related to labor, human rights, and community well-being. This methodological framework allowed for the identification and quantification of key social issues impacting the CSC, with a particular focus on labor conditions, social protection, and health and safety concerns.

Figure *11* explains the proportional distribution of social indicators across various stakeholder categories within the CSC. The Workers category accounts for the largest share (35%), underscoring the paramount significance of employment-related concerns such as job security, wage levels, and labor conditions. Following closely are Value Chain Actors (16%), highlighting their influence in shaping the broader supply chain and its social outcomes. This distribution aligns with the study's focus on addressing the most pertinent social challenges faced by stakeholders in the coffee industry, particularly in terms of fair labor practices, working conditions, and economic stability.

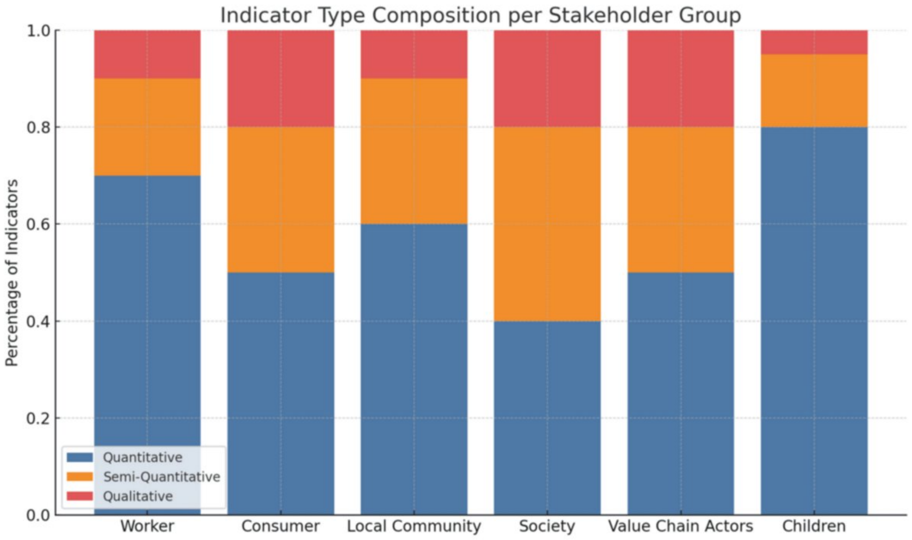


FIGURE 11: Indicators Distribution per Stakeholder Category

Table *15* further elaborates on the typology of the indicators, categorizing them into quantitative, semi-quantitative, and qualitative types for each stakeholder group. For Children and Workers, the majority of indicators are Quantitative (over 70%), indicating that the social issues affecting these groups are more readily quantifiable. These issues include measurable factors such as wage rates, duration of employment, and access to essential services, which can be tracked through numerical data. In contrast, for Consumers and Society, a larger proportion of Qualitative indicators are used. These indicators often pertain to subjective experiences, such as perceptions of fairness, equality, and overall satisfaction with working conditions and social benefits. This divergence in indicator types reflects the varying methodologies required for data collection and analysis based on the stakeholder group in question. The predominance of Quantitative data for certain groups, particularly those directly involved in the workforce, allows for a more robust, objective analysis of their social conditions, while the reliance on Qualitative data for broader societal groups necessitates more interpretive approaches to understanding social impact.

Stakeholder	% Quantitative	% Semi-Quantitative	% Qualitative
Workers	70%	20%	10%
Consumers	50%	30%	20%
Local Community	60%	30%	10%
Society	40%	40%	20%
Value Chain Actors	50%	30%	20%
Children	80%	15%	5%

TABLE 15: Indicator Type Composition Per Stakeholder Group

Figure *12* presented summarizes key responses from the questionnaire, providing insights into the labor conditions, health and safety provisions, and social assessment methods within the CSC. It highlights the methods used to assess and monitor social performance across the industry. The Distribution of Average Daily Wage Levels across respondents reveals that 34.3% of workers earn below the minimum wage, a critical indicator of financial vulnerability and income inequality. This highlights the need for compensation strategies that surpass the minimum wage to address worker financial instability.

The Frequency of OHS Training Provision shows that 57.1% of workers receive occasional OHS training, 22.9% receive regular training, while 20% report no training at all. This gap in OHS education points to significant risks in worker safety and indicates the need for more consistent and comprehensive training to mitigate workplace accidents.

The Monitoring of Child Labor Risk across coffee production sites reveals that no formal monitoring is conducted at most sites. Only 28.6% of respondents report formal audits, and 22.9% mention informal monitoring, highlighting the reliance on ineffective informal methods to address child labor issues. This lack of formal oversight necessitates stronger, more structured child labor monitoring practices.

Regarding Accessibility of Basic Healthcare Facilities for Workers, 71.4% of respondents reported that healthcare is not available. This lack of access to healthcare services for a majority of workers signals the urgent need for policy interventions to ensure health benefits are provided across the supply chain.

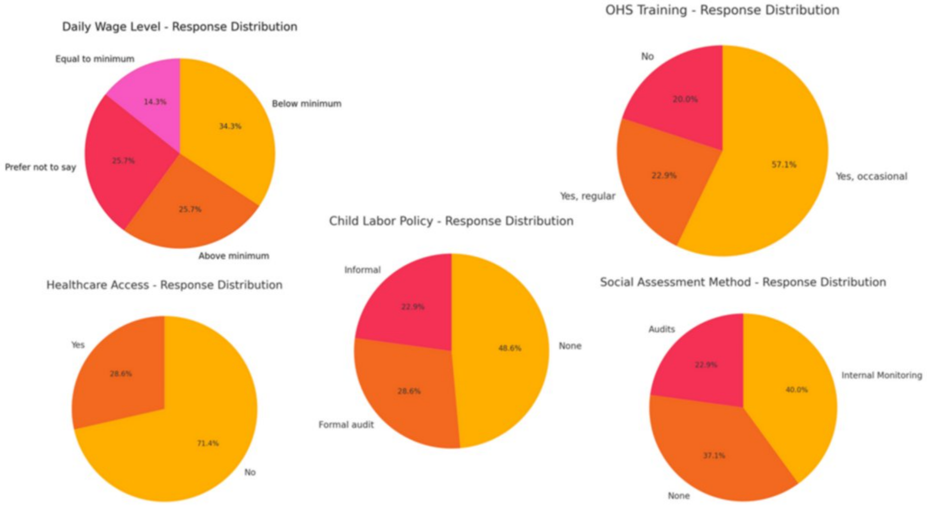


FIGURE 12: Distribution of Responses to Key Social Indicators in Workplace Conditions

The methods used to assess social performance include Internal Monitoring, with 40% of respondents using this approach. Audits account for 22.9% of responses, while 37.1% reported no formal social performance monitoring. This gap in formal auditing practices underscores the need for improved transparency and accountability within the sector.

The technical summary in Table *16* provides the dominant response categories and their percentage share for key indicators.

Indicator	Dominant Response Category	Share (%)
Wage Level	Equal to Minimum Wage	51
OHS Training	Yes, Regularly	46
Child Labor Policy	Informal Monitoring	49
Healthcare Access	Available	71
Social Assessment Method	Internal Monitoring Systems	54

TABLE 16: Technical Summary of Findings

These findings emphasize the necessity of policy reforms and highlight the critical role of internal monitoring systems and audits in improving worker well-being. There is significant potential for improving the formalization of these processes to ensure better social outcomes across the CSC.

These responses were then processed through NVivo 14, where thematic coding and narrative analysis were carried out. Interview responses were inductively coded using open coding techniques and then classified into axial codes across categories such as "Employment Security", "Social Protection Gaps", "Discrimination Risks", and Health and Safety Concerns. Matrix queries were used to quantify response trends across stakeholder types. These themes were further subdivided into specific codes, such as job stability and long-term contracts under Employment Security, or gender and racial discrimination under Discrimination Risks as represented in Figure *13*.

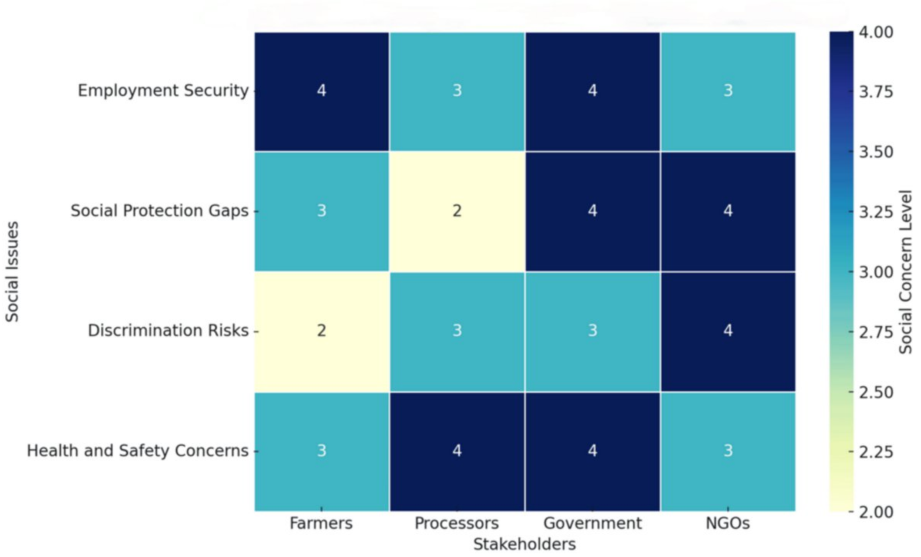


FIGURE 13: Thematic Coding Matrix With Varying Levels of Importance Attributed To Social Issues

The results of the matrix query indicate significant variation in the perceived importance of these social issues. Through these analyses, we found that Employment Security, farmers and processors reported a high concern (4), emphasizing the instability caused by seasonal work and lack of long-term contracts. The Social Protection Gaps theme highlighted a disparity between governmental coverage and the support provided by NGOs, with government respondents acknowledging limited access to social services like health insurance and pensions, while NGOs played a key role in filling the gaps. Discrimination Risks were predominantly highlighted by NGOs and workers, especially regarding gender and racial disparities, where native groups faced barriers to equal pay and employment opportunities. Finally, the Health and Safety Concerns revealed that workers, especially in processing plants, face substantial risks from hazardous chemicals, compounded by inadequate safety training and insufficient enforcement of OHS standards by local governments. This thematic analysis affirms the central role of NGOs and government in addressing these gaps, ensuring fair labor practices, and improving the overall social conditions within the CSC.

The S-LCA model for quantifying social impacts within the CSC was developed using the ANP [42] method in SuperDecisions v2.10. The model structures the system into four main clusters: Social Criteria, Strategic Alternatives, Societal Drivers, and Value Chain Actors, as shown in Figure *14*. Social Criteria encompass key social aspects such as child labor, ethical demand, health and safety, educational access, social empowerment, and wage equity. Value Chain Actors including farmers, processors, NGOs, government, and consumers influence these social criteria. Societal Drivers, such as policy pressure, corporate social responsibility, and access to services, exert further influence on the social criteria. Strategic Alternatives, including labor laws, fair trade initiatives, worker unionization, healthcare access, and education programs, are proposed to improve the social conditions across the supply chain. Connections between actors, drivers, criteria, and alternatives were established to represent interdependencies and feedback loops, thereby enhancing the model's ability to capture the complex dynamics of social sustainability in the coffee value chain. To mitigate subjectivity inherent in expert scoring, we employed a structured approach involving multiple experts from diverse backgrounds in coffee production, social sciences, and supply chain management. Pairwise comparisons and scoring were conducted independently by at least five experts, and consistency ratios were calculated to ensure reliability of judgments. Where inconsistencies were detected, feedback rounds and consensus discussions were held to refine the scoring. This iterative approach reduced individual biases and strengthened the robustness of the social impact model.

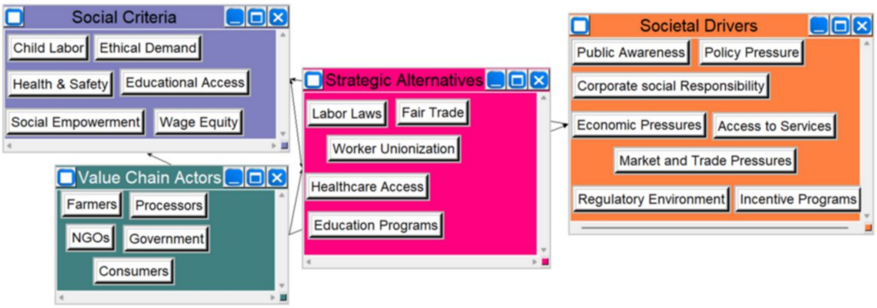


FIGURE 14: Analytical Network Process (ANP) Model for Quantifying Social Impacts in the Coffee Supply Chain

The network was constructed by establishing dependencies between nodes, with pairwise comparison matrices used to assign weights and quantify the relative influence of each value chain actor and alternative with respect to social criteria. The model's robustness was validated through sensitivity analysis, ensuring that the results were reflective of potential real-world scenarios. The results of the synthesis, which were calculated using the ANP method, are summarized in Table *17*.

Alternatives	Ideal Values	Normal Values	Raw Values
Education Programs	1	0.386976	0.193488
Fair Trade	0.319049	0.123465	0.061732
Healthcare Access	0.204074	0.078972	0.039486
Labor Laws	0.689483	0.266814	0.133407
Worker Unionization	0.371531	0.143774	0.071887

TABLE 17: Results of Social Criteria Synthesis Using the ANP Method for Alternative Evaluation

The highest-ranking alternative, Education Programs, was found to have the most significant impact on improving the social conditions related to child labor, educational access, and wage equity in coffee production. Labor Laws also show a strong importance, with a normalized value of 0.266814, highlighting the critical role of enforcing labor regulations in addressing social issues. Worker Unionization and Fair Trade are moderately important, these alternatives offer significant contributions but are relatively less prioritized compared to education programs and labor laws. Finally, Healthcare Access ranks lower among the strategic alternatives, with a normalized value of 0.078972, indicating that while important, healthcare interventions are considered less immediately impactful compared to educational, regulatory, and organizational initiatives. Overall, the analysis shows a clear preference toward educational and legal measures as the primary strategic pathways for enhancing social sustainability in the CSC as shown in Figure *15*.

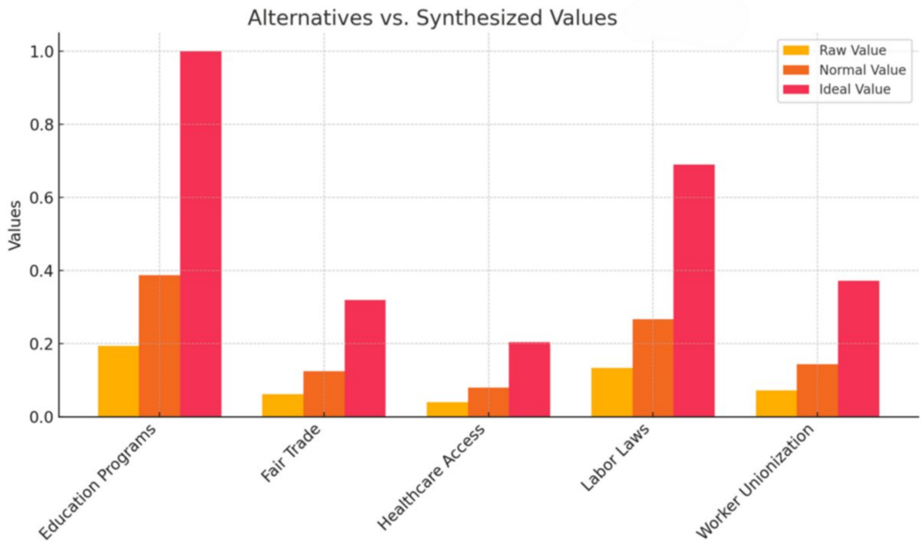


FIGURE 15: Comparative Synthesis of Social Impact Alternatives

Figure *16* depicts the comparison between Normalized Values and Limiting Values for social impact categories where limiting value reveals challenges in its full implementation and the need for strong government regulation to address respective disparities. The significant gap between both values suggests that while these issues are critical, substantial barriers exist in their enforcement and practical application within the supply chain.

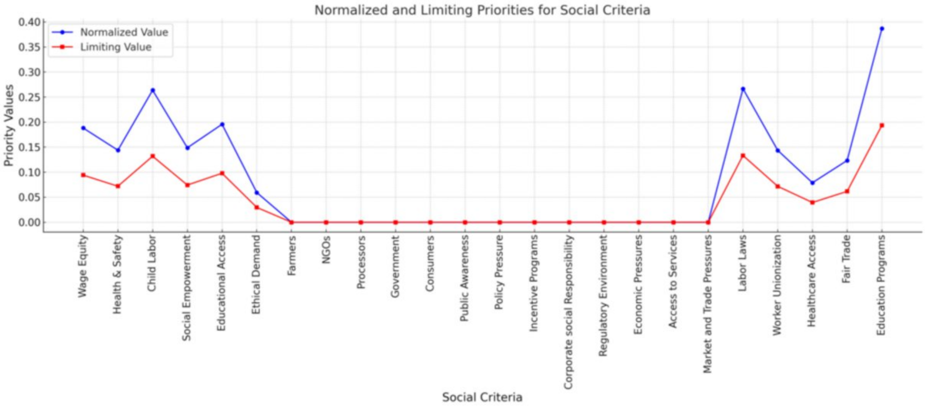


FIGURE 16: Evaluation of Normalized and Limiting Priorities for Social Criteria in the Coffee Supply Chain

The methodological triangulation using SHDB, ANP-based scoring in SuperDecisions, NVivo-supported qualitative coding, and questionnaire responses provides a reproducible framework for embedded social analytics in sustainability research.

Economic life cycle assessment (Econ-LCA)

This section presents the results obtained from the Econ-LCA of the CSC, applying various analytical techniques such as regression modeling, sensitivity analysis, and optimization. These approaches aim to quantify the economic performance at each stage of the supply chain and to identify key economic factors influencing profitability. By incorporating these methods, we derived a comprehensive understanding of how cost management and pricing strategies impact the sustainability and profitability of the coffee industry.

The RF was utilized to model the relationship between various economic factors and the NPM, with the goal of predicting profitability based on variables such as labor costs, transport costs, input costs, gross margin, and MVP. The model's performance was evaluated using several key metrics, including Mean Absolute Error (MAE), Mean Squared Error (MSE), Root Mean Squared Error (RMSE), R^2, Root Mean

Squared Logarithmic Error (RMSLE), and Mean Absolute Percentage Error (MAPE). Each factor's impact on the NPM (%) was assessed by varying it by ±10%. The results for each fold in the cross-validation process, along with the mean and standard deviations, are summarized in Table 18.

Metric	Fold 0	Fold 1	Fold 2	Mean	Std
MAE	1.089	11.584	6.900	6.5243	4.2928
MSE	1.186	134.189	47.610	60.995	55.117
RMSE	1.089	11.584	6.900	6.5243	4.2928
R^2	Nan	Nan	Nan	Nan	Nan
RMSLE	0.0358	0.4393	0.2246	0.2332	0.1649
MAPE	0.0363	0.5792	0.2072	0.2742	0.2266

TABLE 18: Performance Metrics for Random Forest Regressor in Predicting Net Profit Margin (NPM) Using Cross-Validation

R^2 is Nan where the target variable has zero variance (e.g., constant values in test folds).

MSE, Mean Squared Error; RMSE, Root Mean Squared Error; RMSLE, Root Mean Squared Logarithmic Error; MAPE, Mean Absolute Percentage Error

From these results, it is evident that while the model's overall predictive performance (R^2) is weak, the error metrics such as RMSLE and MAPE indicate moderate success in minimizing prediction errors. The relatively low R^2 suggests that the regression model was not fully able to capture the complex relationships between the input variables and the NPM.

The plot in Figure *17a*, illustrating the impact of Gross Margin (USD) on Net Profit Margin (NPM %), demonstrates an inverse relationship, where the NPM begins to decline significantly as the gross margin exceeds 5 USD. This suggests that inefficiencies may begin to outweigh the benefits at higher gross margin levels, indicating that higher gross margins do not necessarily result in higher profitability. Similarly, Figure *17b* reveals a negative correlation between Input Costs (USD) and NPM, showing that as input costs rise above 1.5 USD, the NPM significantly decreases. This highlights the importance of reducing input costs as a key strategy for maximizing profitability in the CSC. Moreover, Figure *17c* shows that Labor Costs (USD) also have a strong negative correlation with NPM, with NPM declining proportionally as labor costs increase. This further emphasizes the need to manage labor expenses to preserve profitability. Finally, in Figure *17d*, we observe that increasing the MVP (USD) leads to a substantial decrease in the NPM, underlining the importance of competitive pricing strategies to maintain robust profit margins, especially in price-sensitive markets. Together, these figures highlight the critical factors and pricing strategies that must be carefully managed to sustain profitability.

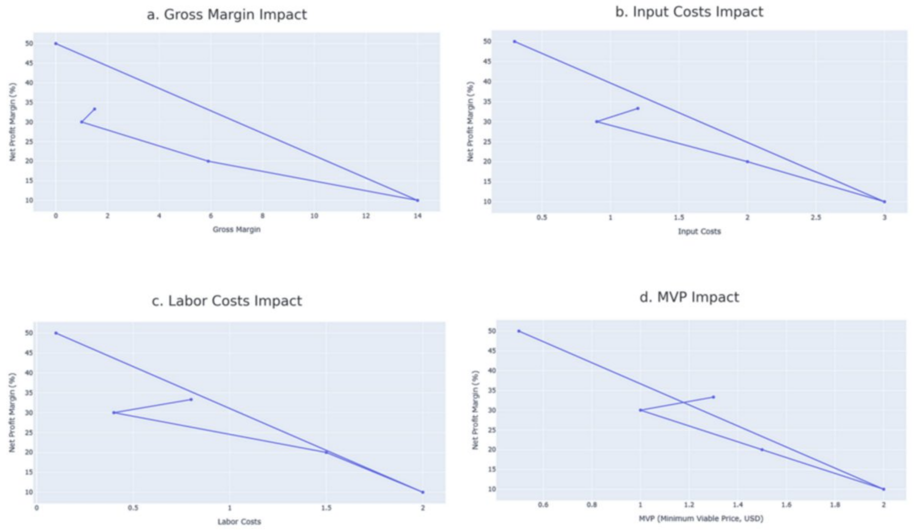


FIGURE 17: Impact of Key Financial Factors on Net Profit Margin (%)

The plot in Figure *18a* demonstrates a clear inverse relationship between processing costs and NPM, where an increase in processing costs leads to a decline in NPM, reinforcing the critical need for cost-efficient production methods to maintain profitability. A similar pattern is observed in Figure *18b*, where higher total costs result in decreased profitability, highlighting the importance of controlling costs at all stages of the CSC to ensure sustainability and maximize returns. Furthermore, Figure *18c* illustrates the impact of transport costs on NPM, further corroborating the negative relationship between rising costs and reduced profitability. As transport costs increase, NPM significantly declines, emphasizing that transportation efficiency is a key contributor to overall profitability in coffee production. Finally, the Volatility Sensitivity analysis in Figure *18d* reveals that high volatility results in reduced profitability, whereas low volatility leads to higher NPM, underlining the importance of maintaining stability in the supply chain and mitigating the effects of market fluctuations. The findings highlight the importance of managing inefficiencies and controlling costs to optimize profitability.

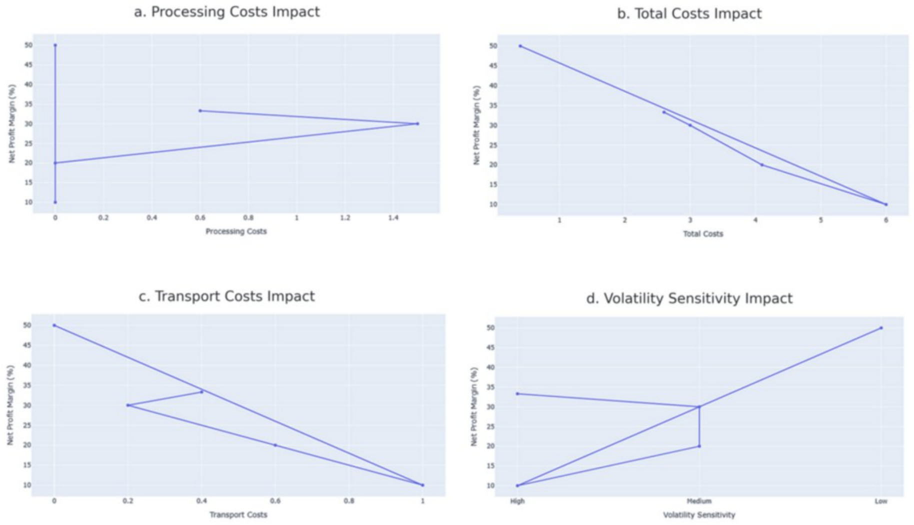


FIGURE 18: Analysis of Cost and Volatility Factors on NPM for Stability in the Market Environment

NPM, Net Profit Margin

Using linear programming techniques with the PuLP and Pyomo libraries, the optimization model was employed to identify the optimal cost structure for labor and transport, aimed at maximizing profitability. The optimized values for labor and transport costs were determined to be 1.0 USD per kilogram for labor and 0.5 USD per kilogram for transport. This cost structure balances the need for cost efficiency with economic viability, ensuring profitability while maintaining cost competitiveness.

The Feature Importance Plot (Figure *19a*), generated using the Random Forest model, highlights the most influential drivers of NPM (%), with MVP (USD) and Total Costs (USD) emerging as the key factors, followed by Gross Margin (USD) and ROI. This analysis emphasizes the factors that should be prioritized to enhance profitability in the CSC. In order to ensure the reliability of the model, Cook's Distance (Figure *19b*) was used to detect any influential data points that could distort the model's performance. The results confirmed that there were no significant outliers, thus ensuring that the model's predictions were not influenced by extreme values. Despite this, the Residuals Plot (Figure *19c*) reveals significant deviations between the predicted and observed values, particularly in the test data. This suggests that the model may be overfitting to the training data and struggling to generalize to new, unseen data. Building on this, the Prediction Error Plot (Figure *19d*) shows a low R^2 value of 0.209, indicating that the model has weak predictive power and is ineffective at capturing the relationship between input features and the target variable. These figures provide a detailed evaluation of the model's strengths and weaknesses, highlighting areas that require improvement.

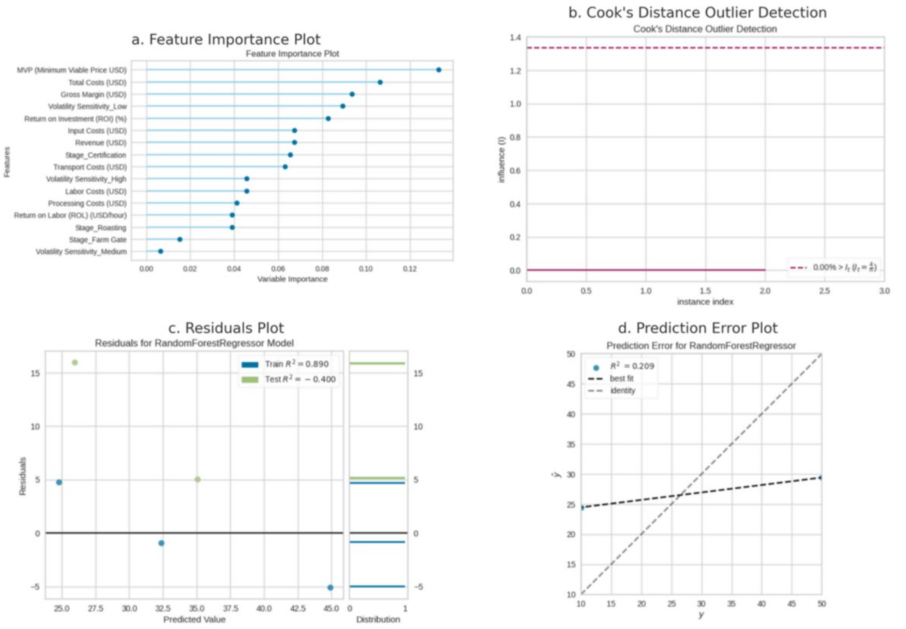


FIGURE 19: Evaluation of Model Performance and Feature Significance

Scenario Analysis and Sensitivity Testing in Econ-LCA

Once data are collected, various scenarios will be simulated to evaluate the impact of fluctuations in key economic factors such as how a 10% increase in labor costs influences profitability, how changes in fuel prices affect margins at various stages of the supply chain, and sensitivity to fertilizer prices, water costs, and other inputs. A sensitivity model is constructed in which these factors are tested under different scenarios. For example, the base case represents current labor, input, and transport costs; the high-cost scenario assumes a 20% increase in input, transport, labor, and other costs; and the low-cost scenario assumes a 20% reduction in these same cost components. These scenarios will allow us to quantify the effects of economic changes on different supply chain stakeholders, such as farmers, processors, and retailers, as depicted in Figure *20b*.

To assess the resilience of the CSC to economic shocks, MVP indicator is used which defines the lowest price at which producers can still cover their costs and remain profitable. This indicator helps assess the financial sustainability of coffee production at various price points. For instance, if the MVP is $1.3 per kg, and coffee prices drop below this threshold, farmers will not be able to cover their costs. Next indicator is sensitivity to Input Costs which evaluates how sensitive profitability changes in input costs such as fertilizers, labor, and water usage as represented in Figure *20a*. This is critical for understanding the financial vulnerability of coffee producers.

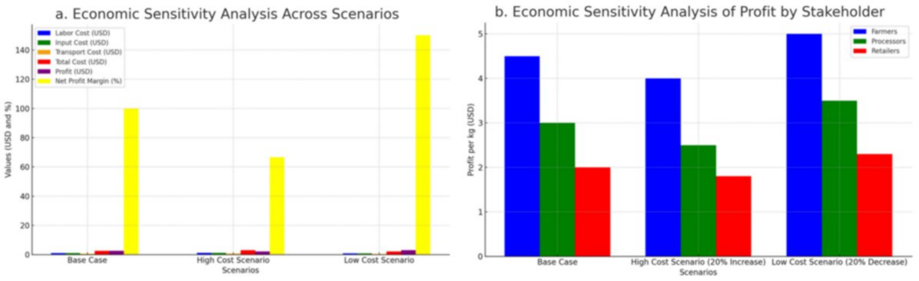
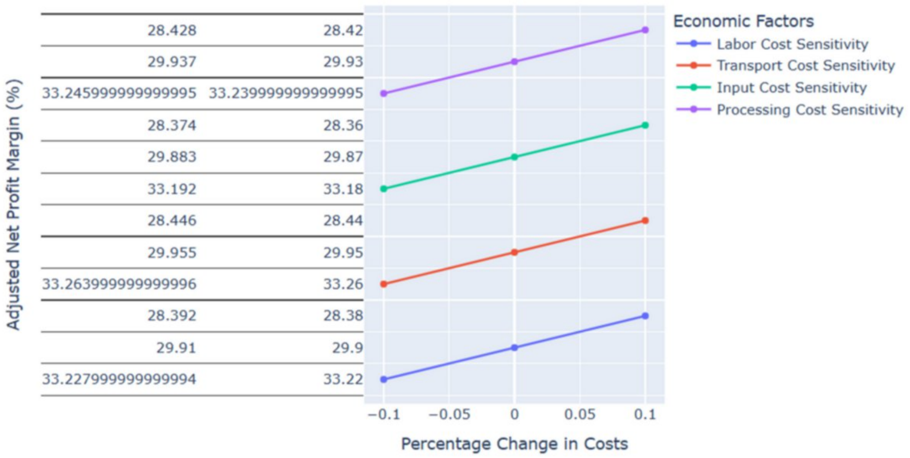


FIGURE 20: Economic Sensitivity Analysis Across Scenarios and Profit by Stakeholder

The charts (Figure *19*) present a sensitivity analysis of the CSC across three economic scenarios. In the Base Case, current cost levels are maintained, resulting in baseline Profit and NPM. The High-Cost Scenario, with a 20% increase in labor and input costs, shows a marked rise in Total Costs, leading to a sharp decline in both Profit and NPM. The Low-Cost Scenario, reflecting a 20% decrease in labor and input costs, results in lower Total Costs and a significant increase in Profit and NPM. This analysis clearly demonstrates that fluctuations in labor and input costs have a direct and substantial impact on profitability. Managing these cost drivers is essential to maintaining financial viability and operational resilience throughout the CSC.

The graph (Figure *21*) shows the Adjusted NPM (%) in response to percentage changes in Labor Cost, Transport Cost, Input Cost, and Processing Cost. Labor cost sensitivity has the greatest impact, with the margin changing by ±0.01%, from 33.24% at a -0.1% change to 33.23% at a +0.1% change. Transport cost sensitivity shows a minimal effect, with the margin fluctuating by ±0.01%, from 33.19% at -0.1% to 33.18% at +0.1%. Input cost sensitivity also results in a ±0.01% change in margin, from 33.19% to 33.18%. Processing cost sensitivity has the smallest effect, with the margin changing by ±0.01%, from 33.22% at -0.1% to 33.23% at +0.1%. Overall, labor costs have the highest sensitivity, while other costs show a relatively small impact on profitability.



28.428	28.42
29.937	29.93
33.245999999999995	33.239999999999995
28.374	28.36
29.883	29.87
33.192	33.18
28.446	28.44
29.955	29.95
33.263999999999996	33.26
28.392	28.38
29.91	29.9
33.227999999999994	33.22

FIGURE 21: Sensitivity Analysis for Economic Factors

Finally, the Validation Curve for RandomForestRegressor displays the relationship between the max_depth of the model and its performance, measured by the Training Score and Cross Validation Score. The plot (Figure *22*) shows that as the max_depth increases from 1 to 10, both the training and cross-validation scores remain consistently around 2.0 for training and 1.0 for cross-validation, suggesting a model that is underfitting. The stability of the scores across all values of max_depth indicates that increasing the depth of the model does not improve performance, and the model's complexity is not benefiting from deeper trees. This suggests that further tuning of hyperparameters, such as max_depth, is required to achieve better generalization.

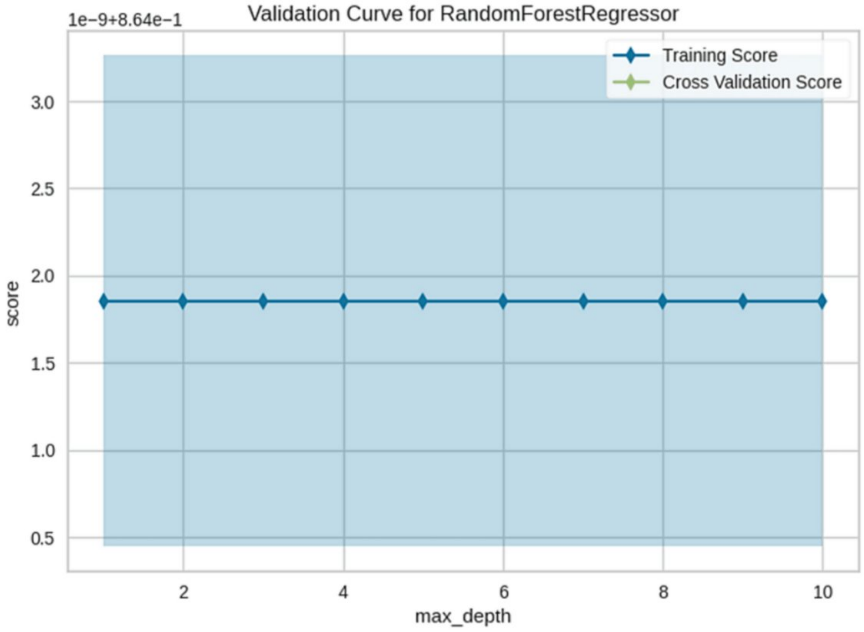


FIGURE 22: Validation Curve for RandomForestRegressor

The application of the Econ-LCA framework to the CSC has yielded valuable insights into the industry's economic dynamics. Regression analysis, sensitivity analysis, and optimization have underscored the critical role of controlling labor, transport, and processing costs to maximize NPM. Optimization results further suggest an ideal cost structure for labor and transport that balances profitability and efficiency. However, the low R² value of the regression model points to its limited predictive power, indicating the need for model refinement. This may involve exploring more complex algorithms or enhancing the data used. Despite these limitations, the sensitivity analysis and feature importance plots provide actionable guidance for strategic cost management and pricing decisions within the CSC.

Outcomes of Natural Capital Assessment (NCA)

The NCA revealed significant insights into the environmental costs and benefits associated with coffee production. By integrating qualitative expert ratings and quantitative proxies, we were able to model the total natural capital value provided by ecosystem services in the CSC.

Qualitative Impact on Ecosystem Services

The integrated LCA scoring Table *19* assesses the sustainability of coffee production by combining economic, social, and environmental indicators, each rated across five levels from highly unfavorable (0-20) to highly favorable (80-100). Economic indicators include labor cost efficiency, which evaluates the balance between labor expenses and production output, and transport efficiency, which measures cost-effectiveness in moving coffee along the supply chain; both are essential for maintaining profitability while minimizing waste. Supply chain transparency, bridging economic and social dimensions, reflects the openness of sourcing, labor conditions, and environmental practices, fostering accountability. Environmental indicators cover energy efficiency in production, water usage efficiency, carbon emissions per unit, and water management practices, all of which address resource conservation and reduction of environmental impact. Soil fertility maintenance assesses fertilizer use where excessive application harms soil health and long-term productivity. Biodiversity impact and pollination support, linked to both environmental and social domains, measure ecosystem integrity and the health of pollinator populations, respectively, both crucial for ecological resilience and crop yield. Social indicators include fair trade and ethical practices, ensuring equitable sourcing and treatment of workers; labor welfare standards, which evaluate working conditions and rights; and health and safety practices, which protect workers from occupational hazards. Together, these indicators provide a comprehensive, multi-dimensional evaluation of sustainability, linking ecological stewardship, social equity, and economic viability.

Qualitative Indicator	Category	Scoring Criteria	(0 to 20)	(20 to 40)	(40 to 60)	(60 to 80)	(80 to100)
Labor Cost Efficiency	Economic	Labor Cost/Unit Output	Very High Cost	High Cost	Reasonable Cost	Low Cost	Extremely Low Cost
Transport Efficiency	Economic	Transport Cost/Unit Output	Very High Cost	High Cost	Moderate Cost	Low Cost	Extremely Low Cost
Energy Efficiency	Environmental	Energy Consumption/Unit Output	Very Inefficient	Inefficient	Reasonably Efficient	Efficient	Highly Efficient
Water Usage Efficiency	Environmental	Water Use/kg Coffee	Very High Usage	High Usage	Moderate Usage	Low Usage	Very Low Usage
CO_2/Unit Output	Environmental	CO_2 Emissions/ kg Coffee	Very High Emissions	High Emissions	Moderate Emissions	Low Emissions	Very Low Emissions
Soil Fertility	Environmental	Fertilizer/kg Coffee	Extremely High	High	Moderate	Low	Negligible
Biodiversity Impact	Environmental/Social	Biodiversity Impact	High Disruption	Moderate Disruption	Low Disruption	Negligible Disruption	No Impact
Pollination Support	Environmental/Social	Pollinator Impact	Significant Decline	Moderate Decline	Slight Decline	Stable	Positive Impact
Fair Trade and Ethical Practices	Social	Degree of Ethical Sourcing	No Ethical Practices	Poor Ethical Practices	Some Ethical Practices	Strong Ethical Practices	Fully Ethical
Supply Chain Management	Social/Economic	Transparency Level	Very Opaque	Opaque	Some Transparency	Mostly Transparent	Fully Transparent
Labor Welfare Standards	Social	Worker Welfare & Safety	Very Poor Standards	Poor Standards	Adequate Standards	Good Standards	Excellent Standards
Water Management Practices	Environmental	Water Recycling Efficiency	No Management	Poor Management	Some Management	Good Management	Excellent Standards

TABLE 19: Integrated Economic, Social, and Environmental Factors Under the Qualitative Scoring System

The chart in Figure *23* illustrates expert panel ratings on various qualitative impact indicators in the CSC, covering both economic and environmental aspects. Labor Cost Efficiency and Transport Efficiency were primarily rated in the moderate (40-60) and high cost (60-80) categories, with 40.3% and 42.9% of responses, respectively. For Water Usage Efficiency, around 75% of ratings fell in the low (60-80) and very low usage (80-100) categories, indicating efficient water use in agroforestry coffee systems. CO_2 emissions per unit output showed positive trends, with 60.1% in the low and very low emissions ranges, reflecting a reduced carbon footprint. Soil Fertility was mostly rated in the low to moderate range (60-80), accounting for 52.5% of responses, suggesting effective nutrient management.

Ratings for Biodiversity and Pollination were concentrated in the low disruption (60-80) and stable (80-100) categories, at 58.2% and 65.4%, respectively, indicating favorable ecological outcomes. Fair Trade and Ethical Practices received strong ratings, with 63.2% falling within the strong (60-80) and fully ethical (80-100) brackets. Supply Chain Management was seen as mostly transparent by 45.3% of respondents, while Labor Welfare Standards were rated good to excellent (60-100) by 59.5%, highlighting decent labor conditions. Overall, the chart reflects significant progress toward sustainability in coffee production, while pointing to ongoing challenges in Transport Efficiency and Labor Cost Efficiency.

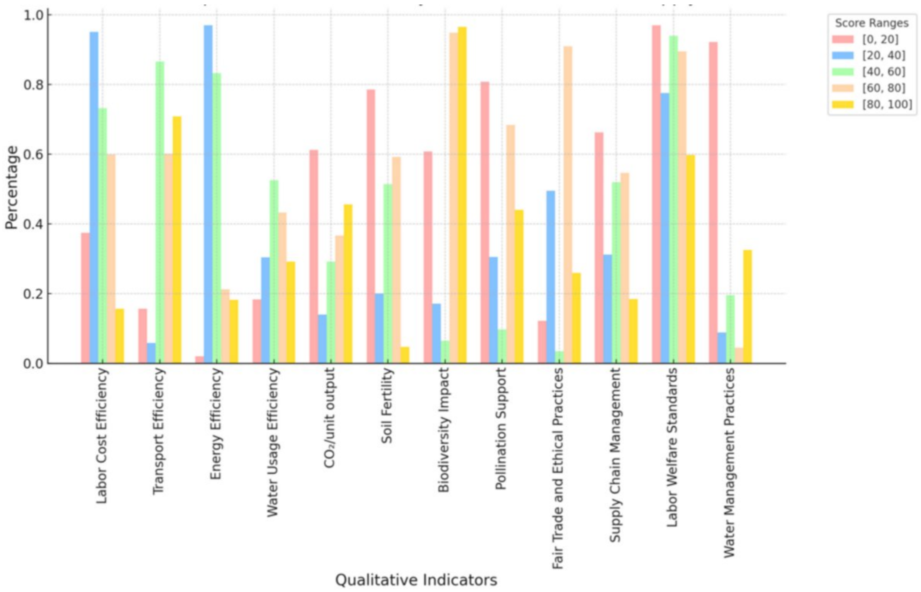


FIGURE 23: Expert Panel Evaluation of Ecosystem Service Indicators in Coffee Production

Analysis and Implications for Quantitative Proxies

The quantitative proxies in the Triple LCA framework are critical for evaluating the environmental impacts of coffee farming, with 5-year trend data revealing progressive adoption of sustainable practices. Figure *24a* suggests that water use efficiency has improved, with consumption declining from 3.8m^3/kg in 2020 to 2.9m^3/kg in 2024, largely due to the implementation of water-saving methods such as drip irrigation and rainwater harvesting, particularly vital in water-scarce regions. Soil fertility trends in Figure *24b* show increased application of nitrogen, phosphorus, and potassium fertilizers, likely aimed at counteracting nutrient depletion and enhancing yields; however, long-term sustainability requires balanced input use, supported by organic farming and agroforestry practices to preserve soil health. Land occupation (Figure *24c*) has also decreased, with total area per hectare falling from 11,000m^2 in 2020 to 10,000m^2 in 2024, indicating more efficient land-use practices driven by intensification, improved crop varieties, and integrated systems like shade-grown coffee. These quantitative indicators support targeted sustainability strategies by demonstrating that optimized resource use and land management can reduce environmental impacts while maintaining productivity, highlighting the importance of integrating environmental, economic, and social dimensions in comprehensive coffee sustainability assessments.

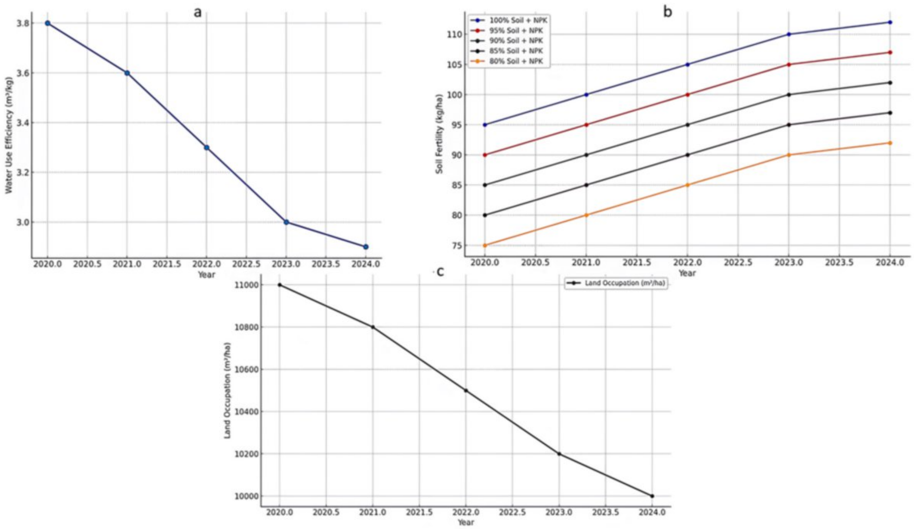


FIGURE 24: Quantitative Assessment of Ecosystem Service Impacts with Temporal Trends in Water Use Efficiency, Soil Nutrient Dynamics, and Land Use Intensity in the Coffee Supply Chain (2020–2024)

The evaluation reveals that shaded agroforestry systems offer considerable ecological advantages, particularly in biodiversity preservation and carbon sequestration. Conversely, the assessment identifies critical challenges, including localized nutrient depletion and elevated water demand in specific production zones. Monoculture-intensive regions exhibited a greater ecological footprint, characterized by increased land use and diminished biodiversity. In contrast, agroforestry-based systems, particularly those with substantial canopy cover, demonstrated enhanced ecological integrity and functioned as effective carbon sinks. These outcomes highlight the imperative for adopting integrated, sustainable production models that align ecological stewardship with economic viability for the coffee sector.

Trade-offs between social, economic, and environmental outcomes

The coffee industry faces significant challenges in balancing social, economic, and environmental outcomes, often in direct conflict. Maximizing yields to meet increasing demand can boost profitability, typically at a ratio of 2:1 to 3:1, but this intensification leads to higher labor stress and biodiversity loss. Technically, these outcomes are interconnected, as higher yields often require more intensive labor, increasing working hours and stress while contributing to environmental degradation through reduced biodiversity. For instance, in monoculture systems, an increase of 1,000 kg/ha in yield can lead to a 20% decrease in biodiversity due to the loss of species richness, while labor stress increases significantly, with working hours rising by 10-15 hours per week for every additional 1,000 kg/ha of yield. The trade-off between these factors can be better understood through the framework of LCA, which quantifies environmental, social, and economic impacts throughout the entire life cycle of coffee production. Ecosystem service trade-offs are quantified using tools like the efficiency frontier, showing how, as yield increases, the biodiversity index decreases exponentially. Similarly, labor stress is modeled using the LIR, which rises as yields increase, reflecting the additional labor demands. The integrated LCA framework helps quantify these trade-offs, demonstrating how intensified farming reduces ecological health and worker welfare, highlighting the need for sustainable practices that balance productivity with long-term environmental and social sustainability.

Trade-Offs Between Yield and Biodiversity Loss

Increased coffee yield is often achieved through intensive farming practices, such as the use of fertilizers, pesticides, and monoculture cultivation. However, these practices typically reduce biodiversity and degrade ecosystem services. To quantify the trade-off between yield maximization and biodiversity, we employ the production possibility frontier, which illustrates the feasible combinations of yield and biodiversity based on ecological constraints (Table 20). The relationship between yield (Y) and biodiversity (B) can be expressed as Equation (2):

$$Y = f(B) \quad (2)$$

Where Y is the yield (kg/ha) and B is the biodiversity index, which can be quantified through species richness (S), the number of species per unit area as given in Equation (3).

$$B = S(A) \quad (3)$$

where A is the land area (ha). The efficiency frontier for coffee production and biodiversity loss follows a concave shape, indicating diminishing returns in biodiversity as yields increase. For example, biodiversity decreases from 50 species per hectare in agroforestry systems to 15 species per hectare in monoculture systems.

Farming System	Yield (kg/ha)	Species Richness (S)	Biodiversity Index (B)
Agroforestry	**1,200**	**50**	**0.45**
Mixed Cultivation	2,500	35	0.28
Monoculture	3,500	15	0.15

TABLE 20: Relationship Between Yield and Biodiversity for Different Farming Systems

The trade-off curve is modeled as Equation (4):

$$Y(B) = \alpha\beta^{-\beta} \quad (4)$$

where α = 5000 and β = 1.5. As yield increases, particularly in monoculture systems, the biodiversity index decreases, reflecting the loss of species richness due to intensive farming practices.

The Figure 25 below shows the trade-off between coffee yield and biodiversity loss across different farming systems. The efficiency frontier curve demonstrates the relationship between the biodiversity index and yield, showing diminishing returns in biodiversity as yields increase. The red dots represent actual data points for Agroforestry, Mixed Cultivation, and Monoculture, with their corresponding yield and biodiversity index values.

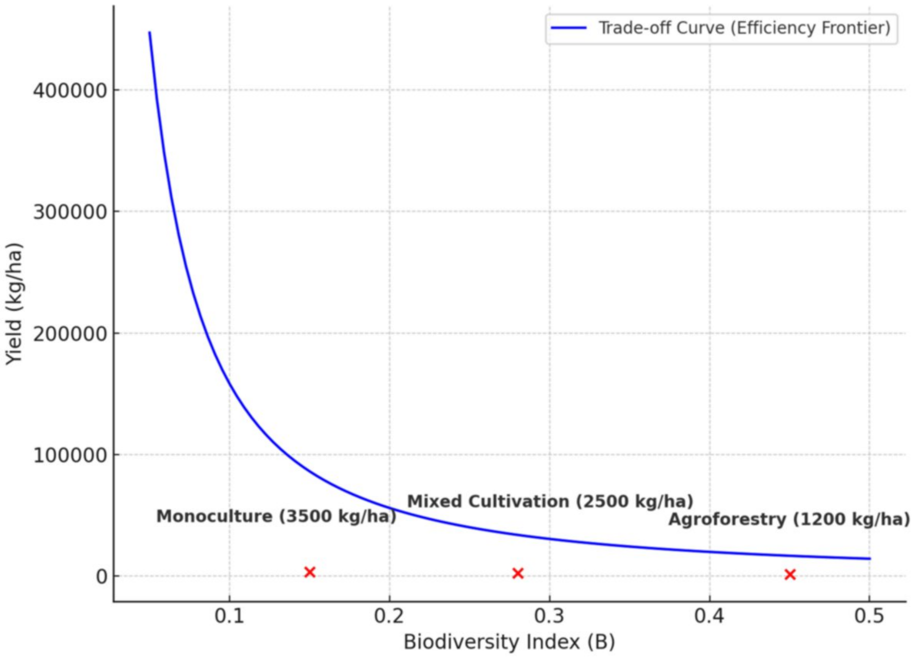


FIGURE 25: Trade-off Between Coffee Yield (kg/ha) and Biodiversity Index (B) as Modeled by the Efficiency Frontier

This Figure emphasizes the need for sustainable practices to balance yield and biodiversity, as further yield increases come at the expense of biodiversity.

Labor Stress vs. Economic Viability

Increasing coffee yields typically requires more labor input, which can lead to labor stress if working conditions deteriorate. A labor stress index (LSI) is introduced to quantify the trade-off between worker well-being and economic outcomes. The index is calculated as Equation (5).

$$LSI = T_w/W \quad (5)$$

where Tw = working hours per day, W = wage rate (USD/hour)

Higher labor stress is often associated with low wages and long working hours. For example, workers on high-yield coffee farms work 12 hours/day during the harvest season, earning $3/hour results in an LSI of 4.00, while those on sustainable farms work 8 hours/day, earning $6/hour has a much lower LSI of 1.33, reflecting better labor conditions and lower stress as depicted in Figure *26b* which highlights the need to balance labor input and economic outcomes to prevent excessive labor stress while maintaining productivity.

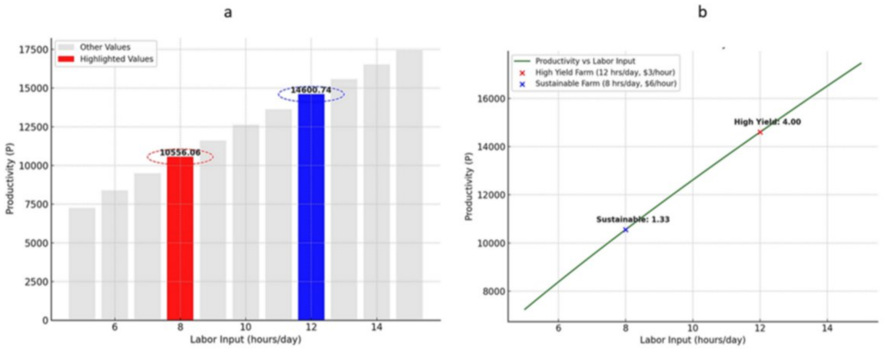


FIGURE 26: Trade-off Between Labor Input and Productivity, Illustrating Labor Stress Impacts on Economic Viability in Coffee Production

The trade-off can be expressed as a function of wages and productivity, where an increase in productivity (P) through intensification leads to higher economic returns but at the cost of worker welfare given as Equation (6).

$$P = \gamma L^{\delta} \quad (6)$$

where L = labor input (hours), γ, δ = parameters

This model in Figure *26a* shows that while increasing L (labor) boosts P (productivity), the marginal utility of labor decreases, meaning that labor stress increases as productivity rises without corresponding increases in wages or welfare.

Economic and Environmental Footprints

The relationship between economic and environmental outcomes can be quantified through the carbon footprint (CF), land use footprint (LF), and water footprint (WF). As highlighted in Scherer et al. (2018), these footprints can be measured per unit of coffee produced as in Equation (7).

$$CF = \sum_i E_i \times GWP_i \quad (7)$$

where E_i= emission from input i, GWP_i = global warming potential of i

Farming System	Yield (kg/ha)	Carbon Footprint (kg CO_2e/ha)	Land Use Footprint (LF) (LSI)	Water Footprint (WF, liters/kg)
Agroforestry	1,200	1,000	0.25	2000
Mixed Cultivation	2,500	2,000	0.45	3000
Monoculture	3,500	3,500	0.65	4500

TABLE 21: Baseline Yield and Associated Carbon, Land Use, and Water Footprints For Three Coffee Farming Systems Per Hectare

From the Table 21, it is clear that monoculture farming results in the highest carbon footprint due to the use of synthetic fertilizers and pesticides. Conversely, agroforestry systems maintain lower carbon footprints while promoting biodiversity.

The land use footprint (LF) can be calculated using the land stress index LSI (Equation 8), which measures the degradation caused by agricultural expansion:

$$LF = \int_A LSI(A)\partial A \quad (8)$$

where A is the area of land used for coffee production.

This analysis emphasizes the need to balance economic outcomes (yield) with environmental impacts (carbon and land use footprints), as higher yields from intensive systems often come at a significant environmental cost as represented in Figure 27.

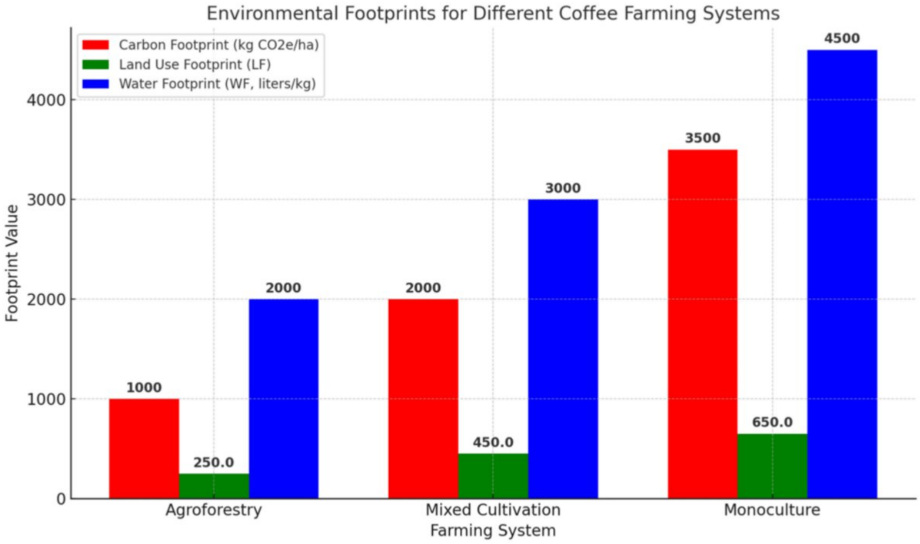


FIGURE 27: Relative Carbon, Land Use, and Water Footprints per Hectare for Agroforestry, Mixed Cultivation, and Monoculture Systems

The economic impact of environmental footprints in coffee farming systems is closely tied to their respective sustainability profiles. Monoculture farming exhibits the highest carbon footprint at 3500 kg CO_2 eq/ha, largely due to intensive use of synthetic fertilizers and pesticides, while Agroforestry shows a significantly lower carbon footprint of 1000 kg CO_2 eq/ha, owing to enhanced carbon sequestration and minimal chemical inputs. Similarly, land use footprint (LF) peaks in Monoculture systems at 0.65, reflecting extensive land stress, whereas Agroforestry and Mixed Cultivation maintain lower LF values of 0.25 and 0.45, respectively, indicating more efficient and sustainable land utilization. Regarding water footprint, Monoculture again ranks highest at 4500 liters/kg, followed by Mixed Cultivation at 3000 liters/kg, and Agroforestry at 2000 liters/kg, with higher usage leading to increased costs and regulatory burdens. Overall, Monoculture imposes the greatest environmental and economic burden, while Agroforestry, despite its lower yield, provides a more balanced and sustainable alternative, with Mixed

Cultivation offering a compromise between productivity and environmental impact.

Relating the environmental footprints to economic factors: Higher environmental footprints increase production costs and reduce profitability, whereas systems with lower footprints have better sustainability and hence cost-efficiency as depicted in Figure 28. To quantify the economic impact of each footprint, a simplified relationship is used such as:

$$E = P - (C_{CF} + C_{LF} + C_{WF}) \quad (9)$$

Where E is the net economic impact (profitability), P is the productivity (yield or profit), C_{CF}, C_{LF}, C_{WF} are the costs associated with carbon, land use, and water footprints, respectively.

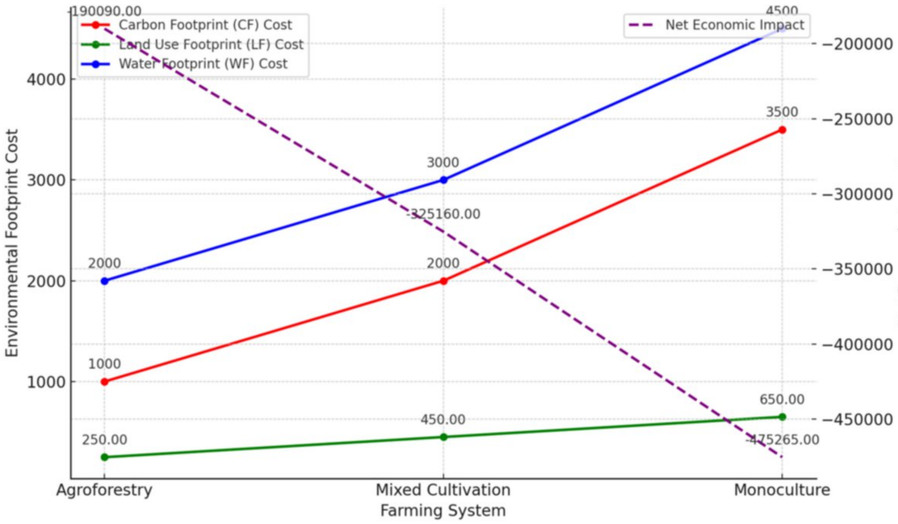


FIGURE 28: Comparison of Environmental Footprint Costs and Net Economic Impact Across Coffee Farming Systems, Highlighting Trade-Offs Between Profitability and Sustainability

Considering the base scenario as CF: €0.10/kg CO_2 eq, LF: €200 per LSI unit and WF: €0.15/m3 and calculating costs from footprints is given in Table 22.

Farming System	CF (kg)	LF (LSI)	WF (m³)	C_CF (€)	C_LF (€)	C_WF (€)	Total Cost (€/ha)
Agroforestry	**1,000**	**0.25**	**2,400**	**€100.00**	**€50.00**	**€360.00**	**€510.00**
Mixed Cultivation	2,000	0.45	7,500	€200.00	€90.00	€1,125.00	€1,415.00
Monoculture	3,500	0.65	15,750	€350.00	€130.00	€2,362.50	€2,842.50

TABLE 22: Estimated Environmental Costs Per Hectare Derived from Carbon, Land Use, And Water Footprints Using Standard Unit Cost Rates

To estimate Economic Profitability (Table 23) market price is set as €1.50/kg of coffee yield to calculate revenue given as Equation (10).

P = Yield(kg/ha)\times \euro 1.50 (10)

Farming System	Yield (kg/ha)	Price/kg (€)	Revenue (P) (€)	Total Cost (€)	Net Profit (E) (€)
Agroforestry	**1,200**	**1.50**	**€1,800**	**€510.00**	**€1,290.00**
Mixed Cultivation	2,500	1.50	€3,750	€1,415.00	€2,335.00
Monoculture	3,500	1.50	€5,250	€2,842.50	€2,407.50

TABLE 23: Calculation of Gross Revenue, Environmental Costs, and Net Economic Impact Per Hectare for Each Farming System Based on Market Yield Value

The pie charts presented in Figure *29* visually represent the proportional distribution of net profit and environmental costs (carbon, land use, and water footprints), which calculates the gross revenue, environmental costs, and net economic impact per hectare for each farming system.

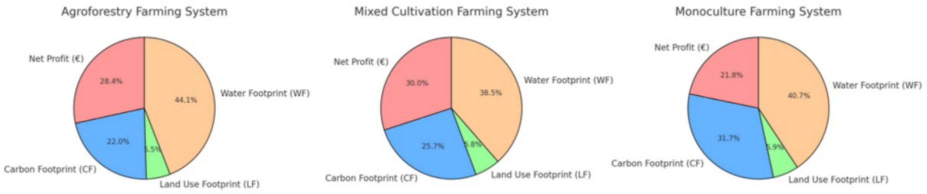


FIGURE 29: Integrated Comparison of Net Profit Alongside Environmental Footprints for Evaluating Sustainability and Economic Efficiency of Farming Systems

These outcomes reveal that although Monoculture farming generates slightly higher revenues, it suffers from significantly elevated environmental costs, particularly in water usage (40.7%) and carbon emissions (31.7%), thus diminishing its overall economic advantage. In contrast, Agroforestry achieves a more balanced profile with the lowest environmental burden, 22% of costs from carbon footprint, while maintaining a viable net profit (28.4%). Mixed Cultivation emerges as a strategic middle ground, delivering solid profitability (30%) with moderate environmental costs, making it a compelling compromise between productivity and sustainability.

Sensitivity and uncertainty in climate predictions in coffee agriculture

The vulnerability of coffee systems to climate change has been extensively modeled under IPCC Representative Concentration Pathways (RCPs). RCP 4.5 and 8.5 scenarios suggest yield declines of 28% in key production regions by 2050, with disproportionate impacts on Arabica varieties due to their temperature sensitivity [43]. In addition, water demand for irrigation and processing is expected to increase by over 41%, exacerbating stress on water systems and smallholder livelihoods [44]. These projections are summarized in Table *24*, which also outlines associated social and economic risks such as increased labor burdens and income loss.

Climate Scenario	Yield Change (%)	Water Demand Change (%)	Social Impact	Economic Risk
RCP 4.5	−15%	+25%	Medium	Moderate Income Loss
RCP 8.5	−28%	+41%	High (Labor Burden, Migration)	Severe Market Disruptions

TABLE 24: Climate Scenario Impacts on Coffee Production (RCP 4.5 vs 8.5)

Refer to reference [45].

Figure *30* presents a visual trajectory of yield and water demand under both scenarios. Matplotlib (Python) is used to analyze how climate scenarios affect agricultural productivity and water resources over time, aiding policy-making and planning, particularly for future climate change impacts on food security and water conservation. The trend lines emphasize the disproportionate impact on Arabica coffee and smallholder viability, reinforcing the need for anticipatory adaptation strategies within the CSC. Although several predictive models exist, ranging from DSSAT, AquaCrop, to AgMIP, few studies have linked these projections with economic and social impact assessments. There is a critical need to simulate not only ecological changes but also their cascading effects on labor burden, household income, and supply chain resilience. Integrating scenario modeling into LCSA can help fill this predictive and policy-relevant gap.

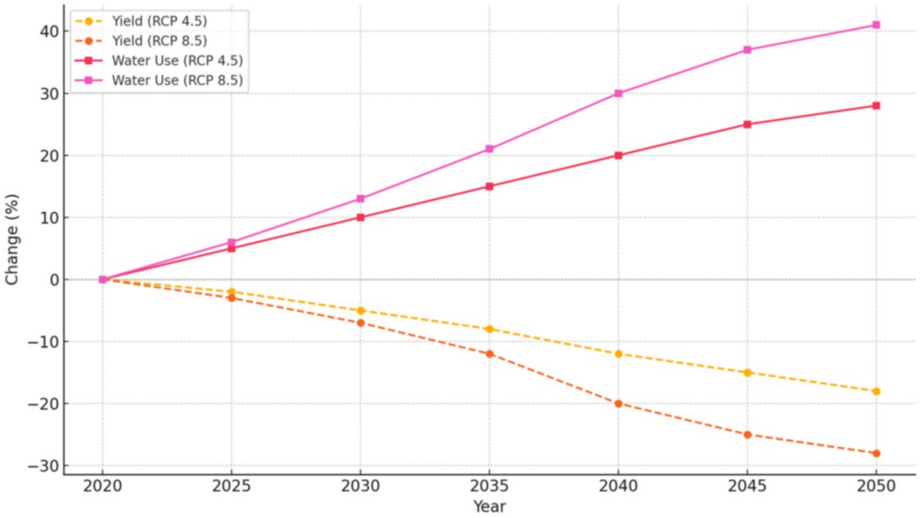


FIGURE 30: Projected Yield and Water Use Under Both RCPs Through 2050

Discussion

Comprehensive sustainability assessment through Triple-LCA methodology

Our study contributes significantly to the existing body of literature by utilizing the Triple-LCA methodology to provide a comprehensive evaluation of coffee farming sustainability. In comparison to previous research, such as the study by Xia and Wei [46], which mainly explored environmental impacts such as carbon emissions and land use in monoculture systems, our study expands the analysis by also incorporating social dimensions, such as worker welfare, income distribution, and labor conditions. For instance, while monoculture systems show significant carbon emissions with 2,873 kg CO_2eq/ha on average as shown by Densley et al., and similarly as observed in our study 3,500 kg CO_2eq/ha, these systems also contribute to increased labor stress and income disparity among smallholders [47]. In contrast, agroforestry systems, with 1,200 kg/ha of yield, offer lower yields but provide greater long-term sustainability and economic stability by improving soil health, water retention, and reducing the need for costly inputs like synthetic fertilizers. By integrating social aspects, we also show how agroforestry and mixed cultivation systems not only reduce carbon footprints (by up to 20%, as reported by Coffee Certification Data Report 2021 Rainforest Alliance and UTZ Programs (2022) but also improve labor conditions and offer higher wages to workers, in contrast to the intensive labor demands of monoculture systems [48].

Furthermore, economic sustainability has been traditionally examined in studies such as Berihun and Gutema, who highlighted that certification schemes help increase the income of smallholder coffee farmers [49]. Our findings provide empirical evidence showing that certified systems, such as agroforestry, result in both lower environmental impacts (e.g., 20% lower carbon emissions) and improved labor outcomes, but that these systems still face barriers in terms of market access and high certification costs.

Mitigating the trade-offs between environmental, social, and economic outcomes

Our findings suggest that sustainable farming practices, particularly agroforestry and organic coffee farming, offer a viable path to mitigate the trade-offs between environmental, social, and economic outcomes. These systems, as demonstrated in Honduras and Costa Rica, show significant environmental benefits, including lower carbon footprints, better long-term yields and improved soil health, compared to intensive monoculture systems. The adoption of agroforestry provides social benefits, such as better labor conditions and higher wages for farm workers due to the less intensive labor demands during harvest. These outcomes align with findings from references [50-53], where researchers found that agroforestry systems provided a better balance between biodiversity conservation and economic outcomes compared to monoculture systems.

In contrast, monoculture coffee farming, while yielding higher quantities, comes at the cost of environmental degradation, including loss of biodiversity and soil fertility, which ultimately threatens long-term economic sustainability. This is supported by Haro et al., who highlighted the diminishing returns in biodiversity as yield increases in monoculture systems [53]. Our study echoes this finding, showing a direct trade-off between yield maximization and environmental sustainability, with monoculture systems contributing significantly to carbon emissions and land use degradation.

The role of certification schemes in promoting sustainability

Certification schemes such as Fairtrade and Rainforest Alliance play a crucial role in promoting sustainable practices and enhancing market access for smallholders. Our results demonstrate that Fairtrade-certified farmers earn, on average, 30% higher incomes than their non-certified counterparts, reflecting the financial benefits of certification. This finding is consistent with researchers [54], who reported similar income improvements for farmers participating in certification schemes in Latin America.

However, the uptake of certification schemes remains slow, particularly among smallholder farmers, due to the high costs of certification and the top-down nature of many certification processes [55]. As observed in our study, while certifications improve social outcomes by ensuring fair wages and better working conditions, they do not fully address the income disparity between farmers and retailers. For example, coffee farmers in Italy continue to receive only 10-12% of the final price, a figure that has been stable for decades, highlighting the need for greater integration of farmers into the value chain [10].

Our findings suggest that policy support is critical to making certification schemes more accessible. Governments can incentivize smallholder participation by providing subsidies for certification and technical assistance to help farmers meet the standards. This aligns with the recommendations from Sayekti and Prihandono, who emphasizes the importance of government intervention in reducing the barriers to entry for smallholders in certification schemes [56].

Policy recommendations and industry partnerships for sustainable coffee farming

The results from our study underscore the importance of policy frameworks that integrate economic, environmental, and social goals. Governments should introduce policies that incentivize the adoption of sustainable practices, such as subsidies for low-carbon technologies (e.g., solar-powered irrigation), and financial support for agroforestry systems. These policies would reduce the environmental footprint of coffee production while improving the economic viability of smallholder farmers.

Industry partnerships also play a pivotal role in supporting smallholders. By collaborating with research institutes like the International Center for Tropical Agriculture (CIAT), coffee traders, and retailers, the coffee industry can help facilitate the transition to sustainable farming practices. Our findings are in line with the work of Maryono et al., who emphasize the importance of multi-stakeholder partnerships in promoting sustainable agricultural practices [57]. Industry players such as Nestlé and Starbucks have already committed to sourcing 100% certified sustainable coffee by 2025 [58]. These partnerships provide smallholders with training, market access, and financial incentives, thereby reducing the economic burden of transitioning to sustainable coffee production. In Colombia, a government-backed financing scheme has helped over 500 coffee cooperatives adopt sustainable farming practices, resulting in increased productivity and access to international markets [59].

Our study suggests that to further enhance the effectiveness of these initiatives, there must be policy coherence between national coffee production strategies and global sustainability goals, such as those outlined in the SDGs. Specifically, we target SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 1 (No Poverty) through our proposed policies and strategies, which aim to reduce the environmental impact of coffee farming while improving the social and economic conditions of smallholder farmers. Furthermore, international organizations like the UN can play a pivotal role in fostering cross-country partnerships to enhance global coffee sustainability. Collaborative funding and shared risk management mechanisms are crucial to help smallholders transition to more sustainable farming practices.

Limitations and uncertainties of the triple LCA approach

Although our Triple-LCA framework offers a comprehensive sustainability assessment, each LCA stream presents inherent limitations and uncertainties that should be acknowledged.

Environmental LCA (E-LCA): The accuracy of environmental impact estimates depends on data quality and system boundary definitions. Our reliance on available emission factors and footprint data may not capture all regional variabilities, such as microclimatic differences or site-specific management practices, which can affect carbon, water, and land-use assessments.

Social LCA (S-LCA): Social impacts are intrinsically complex and context-dependent, often relying on qualitative data and stakeholder perceptions. Despite efforts to ensure representativeness through interviews and secondary data, some social indicators may suffer from limited data availability, potential respondent bias, and difficulties in quantifying social outcomes consistently across regions and actors.

Economic LCA (Econ-LCA): Economic assessments involve uncertainties related to market price fluctuations, cost assumptions, and income estimations. This economic model assumes fixed market prices and standard unit costs, which may not fully reflect dynamic market conditions or informal economic activities prevalent among smallholders.

While the findings are grounded in the Italian market context, characterized by high consumption, value capture in roasting, and premium pricing, many of the identified sustainability trade-offs, particularly in farming systems, have broader relevance. However, generalization to other regions should account for differences in consumption patterns, supply chain structures, and regulatory environments. Acknowledging these limitations highlight the need for continuous data refinement, integration of localized and longitudinal datasets, and the development of dynamic modeling approaches to enhance future Triple-LCA applications.

Conclusions

This study provides a Triple LCA analysis of the coffee value chain in Italy, integrating environmental, social, and economic factors to offer a comprehensive sustainability assessment. The environmental findings reveal that coffee cultivation accounts for 95% of water use (39.01 m^3/kg roasted coffee) and 80% of land use, along with significant contributions to acidification (4.095 mol H^+ eq) and climate change (511.28 kg CO_2-eq). Roasting contributes 7.56 kg CO_2-eq to climate change, and the adoption of sustainable practices, such as organic farming and biowaste valorization, could reduce GHG emissions from 3.5 kg CO_2-eq to 0.62 kg CO_2-eq per kg of roasted coffee, highlighting the potential for environmental improvements. In parallel, the social analysis reveals that 34.3% of workers earn below minimum wage, 57.1% receive occasional OHS training and educational services, and 71.4% lack access to healthcare, indicating significant gaps in labor conditions and the pressing need for stronger monitoring systems and social protection. The economic analysis further underscores these disparities, showing that smallholders earn only $0.60 per kg of conventional coffee, while roasted coffee in Italy retails for EUR 20/kg, with roasters capturing a significant portion of the value (20% margin) compared to only 10% for smallholders. Sensitivity analysis indicates that a 10% increase in labor costs reduces NPM by 0.1%, while a 20% reduction in input costs increases NPM by 0.5%, highlighting the economic vulnerability of smallholders. Furthermore, Natural Capital Accounting reveals significant risks to biodiversity and soil fertility due to monoculture systems, with key ecosystem services like pollination and carbon sequestration being crucial for long-term coffee production sustainability. These findings emphasize the importance of integrating environmental, social, and economic dimensions in sustainability assessments. However, the study's limitations lie in its reliance on existing data, which may not fully represent the diverse conditions across different coffee-growing regions, especially informal smallholder farms. While this study provides a strong static assessment, future research should enhance dynamic modeling by incorporating climate projections (e.g., temperature shifts, rainfall variability) and long-term yield sensitivity under different scenarios. Improving feature engineering in predictive models such as integrating variables related to farm-level adaptation capacity, ecosystem service thresholds, and socio-economic resilience can increase the accuracy and policy relevance of sustainability projections. Such advances will strengthen the operational utility of Triple-LCA and NCA for long-term planning in climate-sensitive agricultural systems. Future work should also focus on incorporating more detailed socio-economic data from smallholders, refining predictive climate models to estimate coffee yield reductions under different climate scenarios, and further assessing the economic resilience of various farming systems. The Triple-LCA and NCA framework presented is designed to be adaptable and scalable for other commodities, such as cocoa and tea, especially within similar EU market contexts. Applying this methodology to other value chains will require changing of specific social, environmental, and economic indicators relevant to each commodity's production systems and market dynamics. Moreover, integrating more granular data on ecosystem services, particularly for biodiverse farming systems like agroforestry, will strengthen the robustness of future sustainability assessments. To translate these findings into actionable outcomes, targeted policy interventions are essential. Financial incentives, such as subsidies or tax relief, can support farmers adopting low-impact practices like organic farming and biogas utilization. Payment schemes for ecosystem services can help internalize environmental costs and reward biodiversity protection, soil conservation, and carbon sequestration. Strengthening traceability systems and certification mechanisms can promote transparency and reward sustainable practices across the supply chain. Finally, training programs and cooperative support structures are necessary to reduce the economic vulnerability of smallholders while enabling a fairer distribution of value. These measures, supported by national and EU-level agricultural policy, will enhance the scalability and impact of integrated sustainability frameworks in coffee production

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Antonella Petrillo, Fabio De Felice, Mizna Rehman

Acquisition, analysis, or interpretation of data: Antonella Petrillo, Fabio De Felice, Mizna Rehman

Drafting of the manuscript: Antonella Petrillo, Fabio De Felice, Mizna Rehman

Critical review of the manuscript for important intellectual content: Antonella Petrillo, Fabio De Felice, Mizna Rehman

Supervision: Antonella Petrillo, Fabio De Felice

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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